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(54) **APPARATUS AND METHOD FOR RANGING AND NOISE REDUCTION OF LOW COHERENCE INTERFEROMETRY LCI AND OPTICAL COHERENCE TOMOGRAPHY OCT SIGNALS BY PARALLEL DETECTION OF SPECTRAL BANDS**

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See application file for complete search history.

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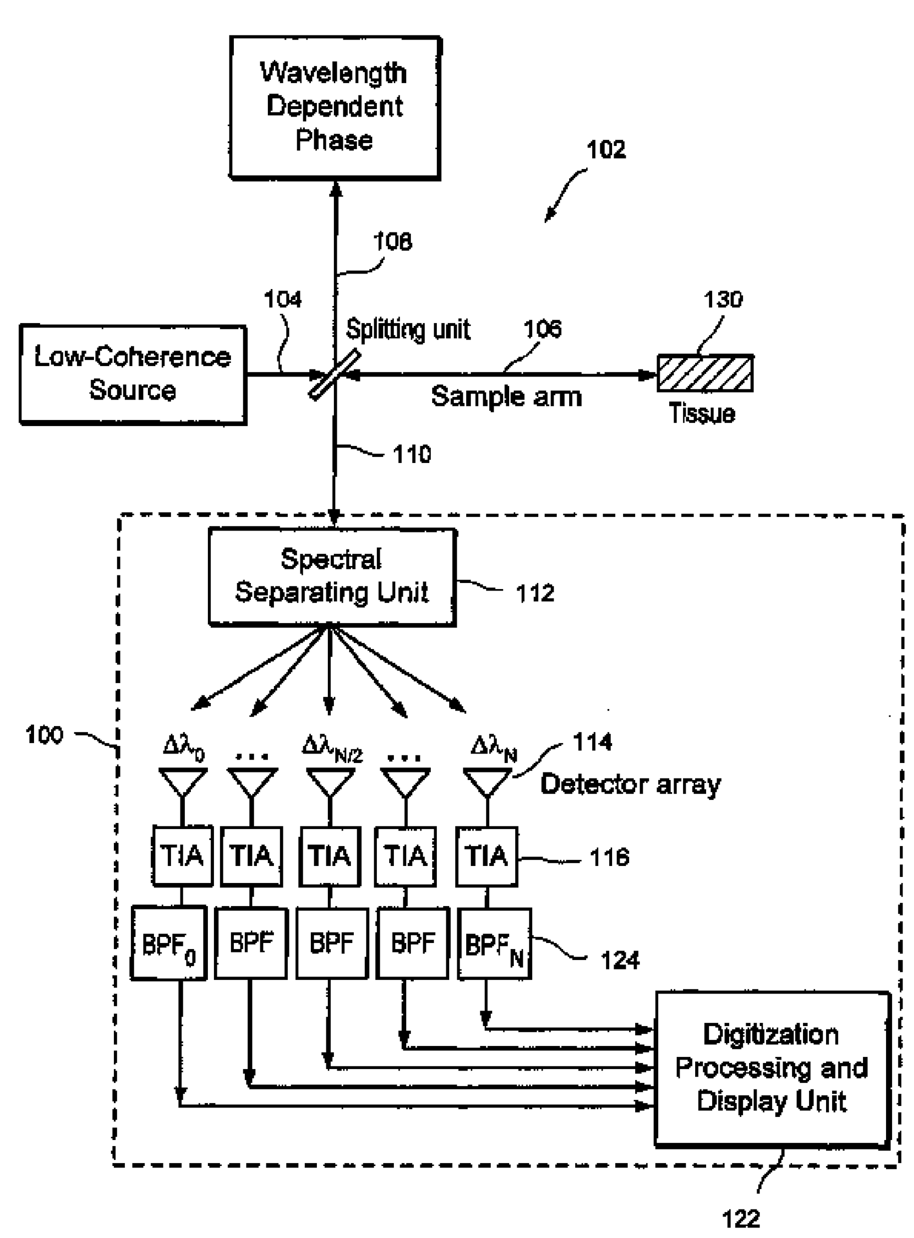
(57) **ABSTRACT**

Apparatus and method for increasing the sensitivity in the detection of optical coherence tomography and low coherence interferometry ("LCI") signals by detecting a parallel set of spectral bands, each band being a unique combination of optical frequencies. The LCI broad bandwidth source is split into N spectral bands. The N spectral bands are individually detected and processed to provide an increase in the signal-to-noise ratio by a factor of N. Each spectral band is detected by a separate photo detector and amplified. For each spectral band the signal is band pass filtered around the signal band by analog electronics and digitized, or, alternatively, the signal may be digitized and band pass filtered in software. As a consequence, the shot noise contribution to the signal is reduced by a factor equal to the number of spectral bands. The signal remains the same. The reduction of the shot noise increases the dynamic range and sensitivity of the system.

10 Claims, 19 Drawing Sheets



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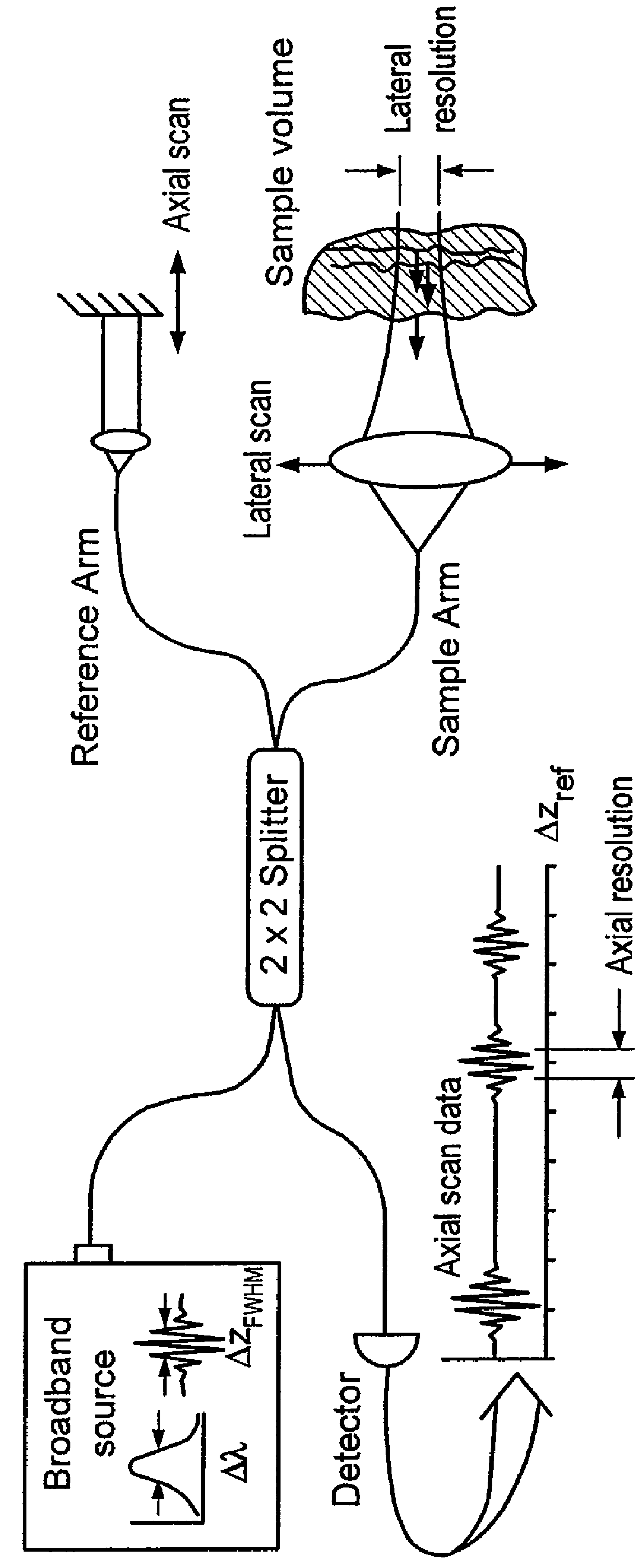
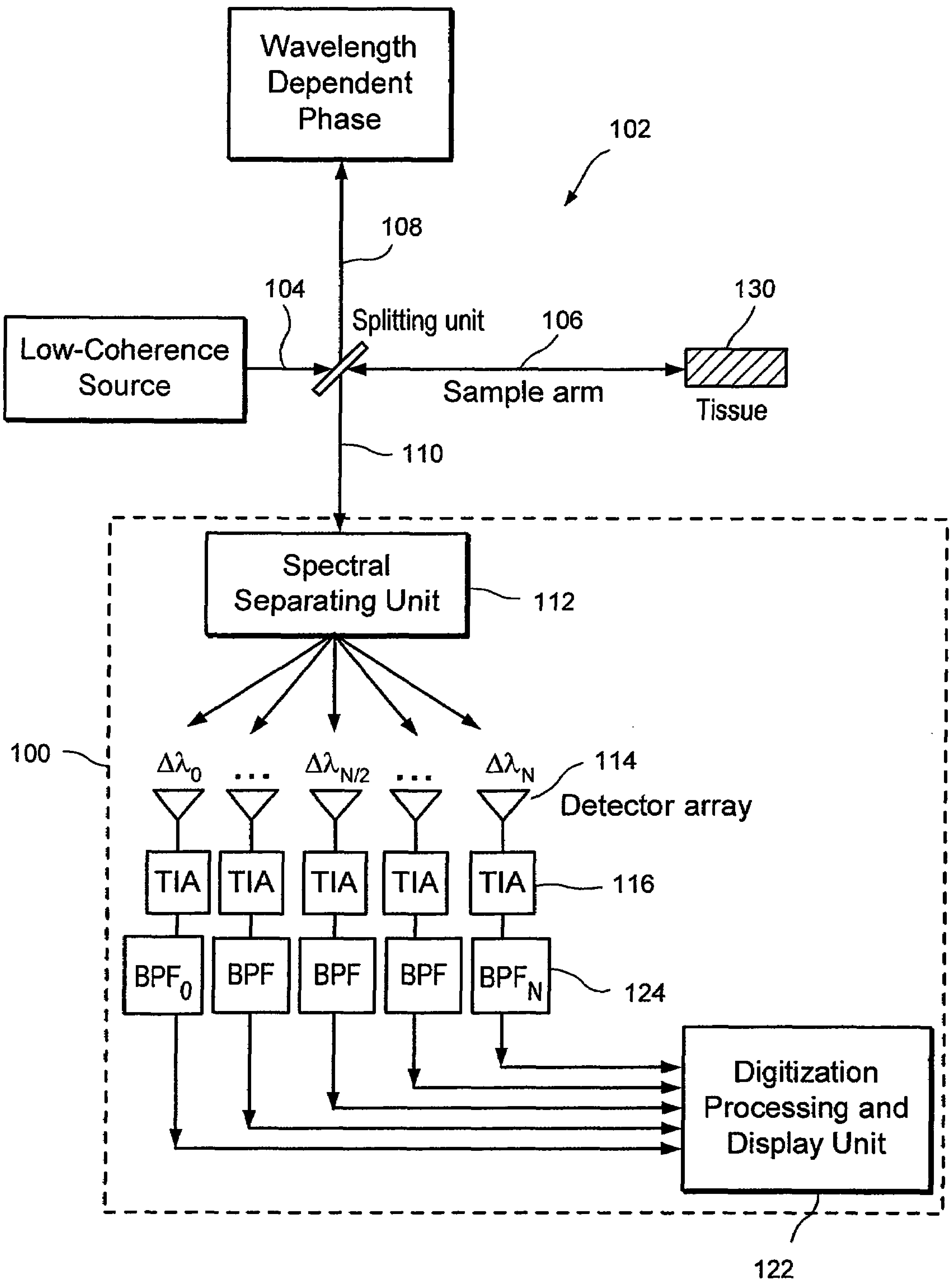
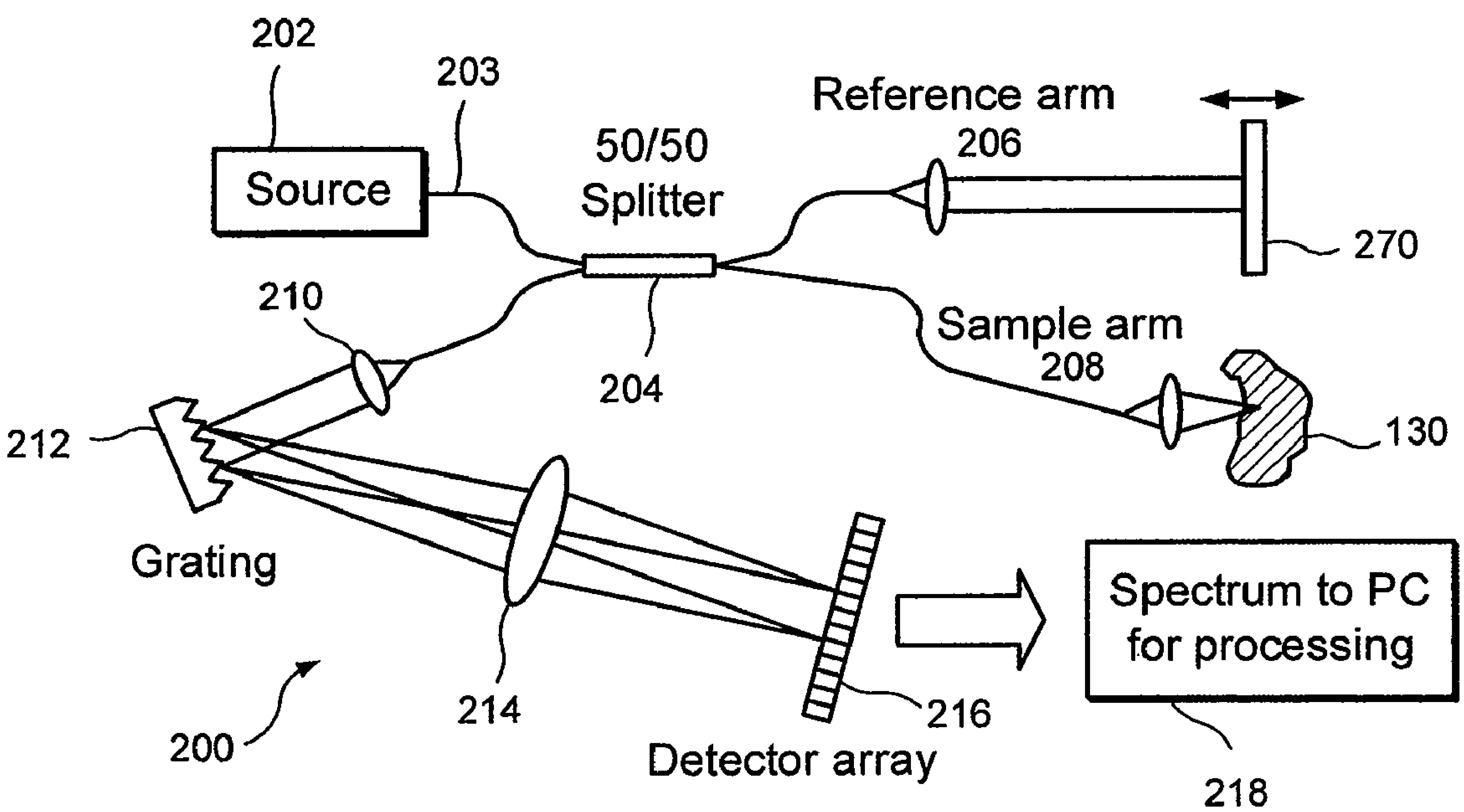

Axial scan
Sample volume
Lateral
resolution
Lateral scan
Reference Arm
Sample Arm
2 x 2 Splitter
Broadband
source
$\Delta\lambda$
Δz_{FWHM}
Detector
Axial scan data
Axial resolution
Δz_{ref}

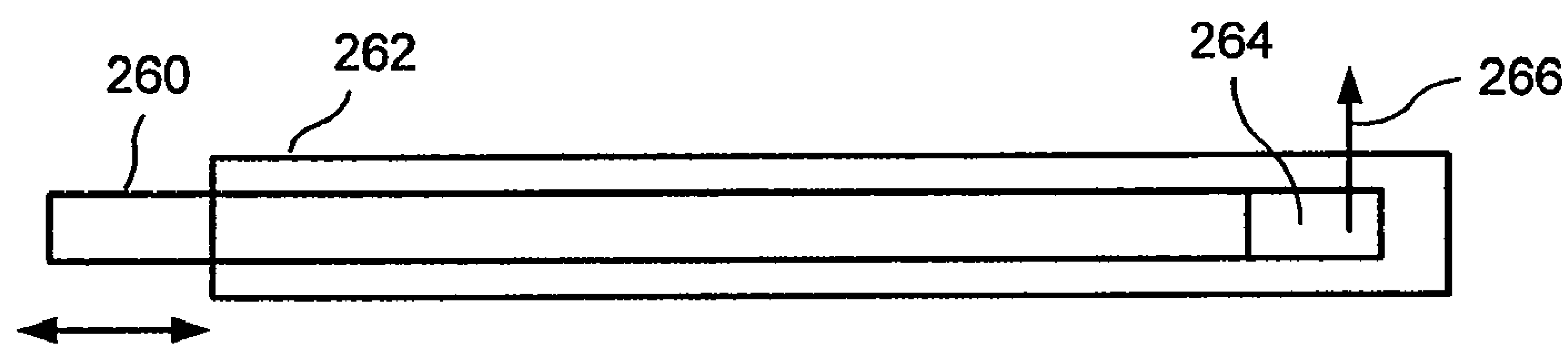
F I G. 1


Wavelength
Dependent
Phase
102
108
104
Splitting unit
106
130
Low-Coherence
Source
Sample arm
Tissue
110
Spectral
Separating Unit
112
100
$\Delta\lambda_0$
...
$\Delta\lambda_{N/2}$
...
$\Delta\lambda_N$
114
Detector array
TIA
TIA
TIA
TIA
TIA
116
BPF_0
BPF
BPF
BPF
BPF_N
124
Digitization
Processing and
Display Unit
122

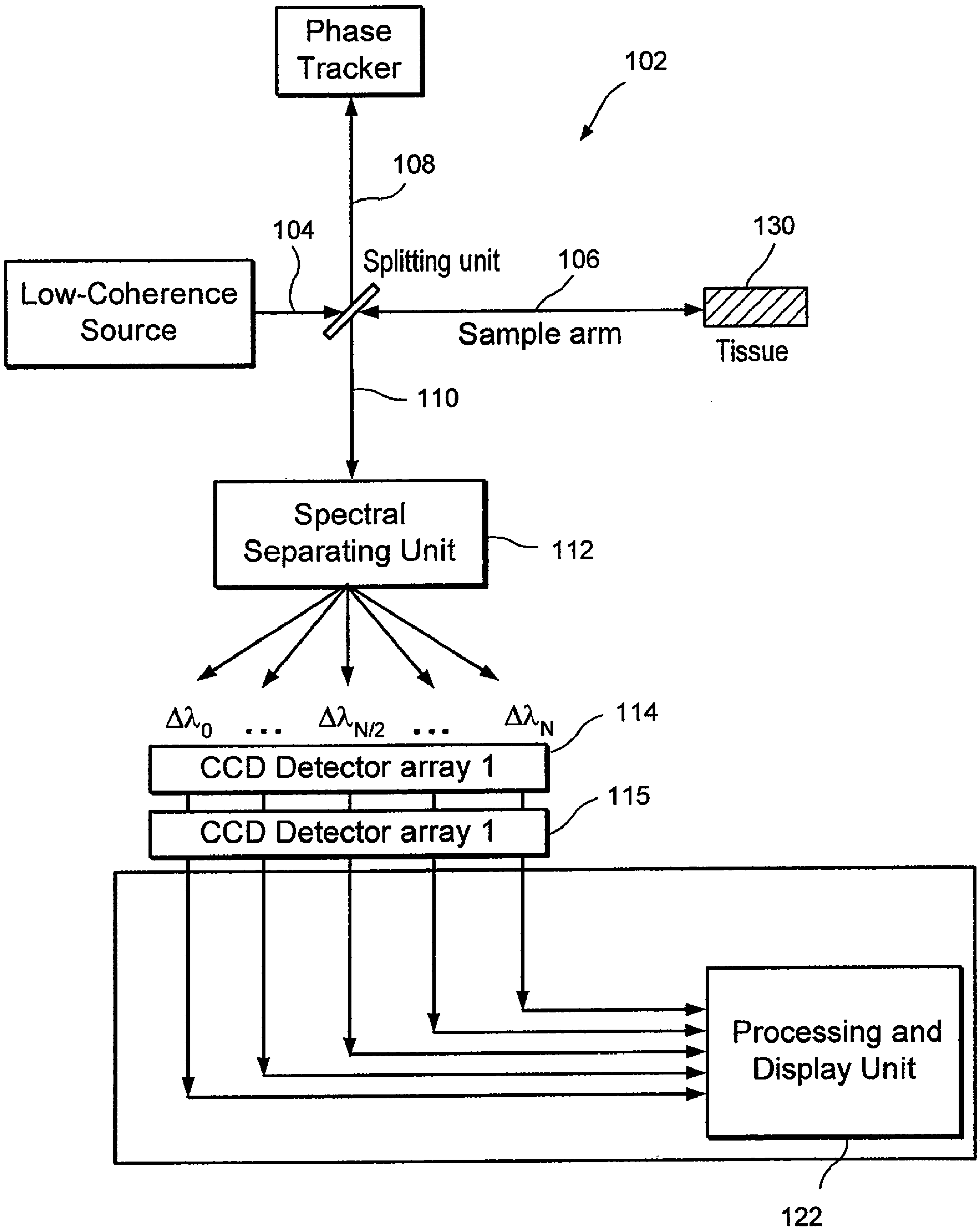
F I G. 2


202
203
Source
50/50
Splitter
Reference arm
206
270
210
204
Sample arm
208
212
130
Grating
Spectrum to PC
for processing
200
214
216
Detector array
218

F I G. 3

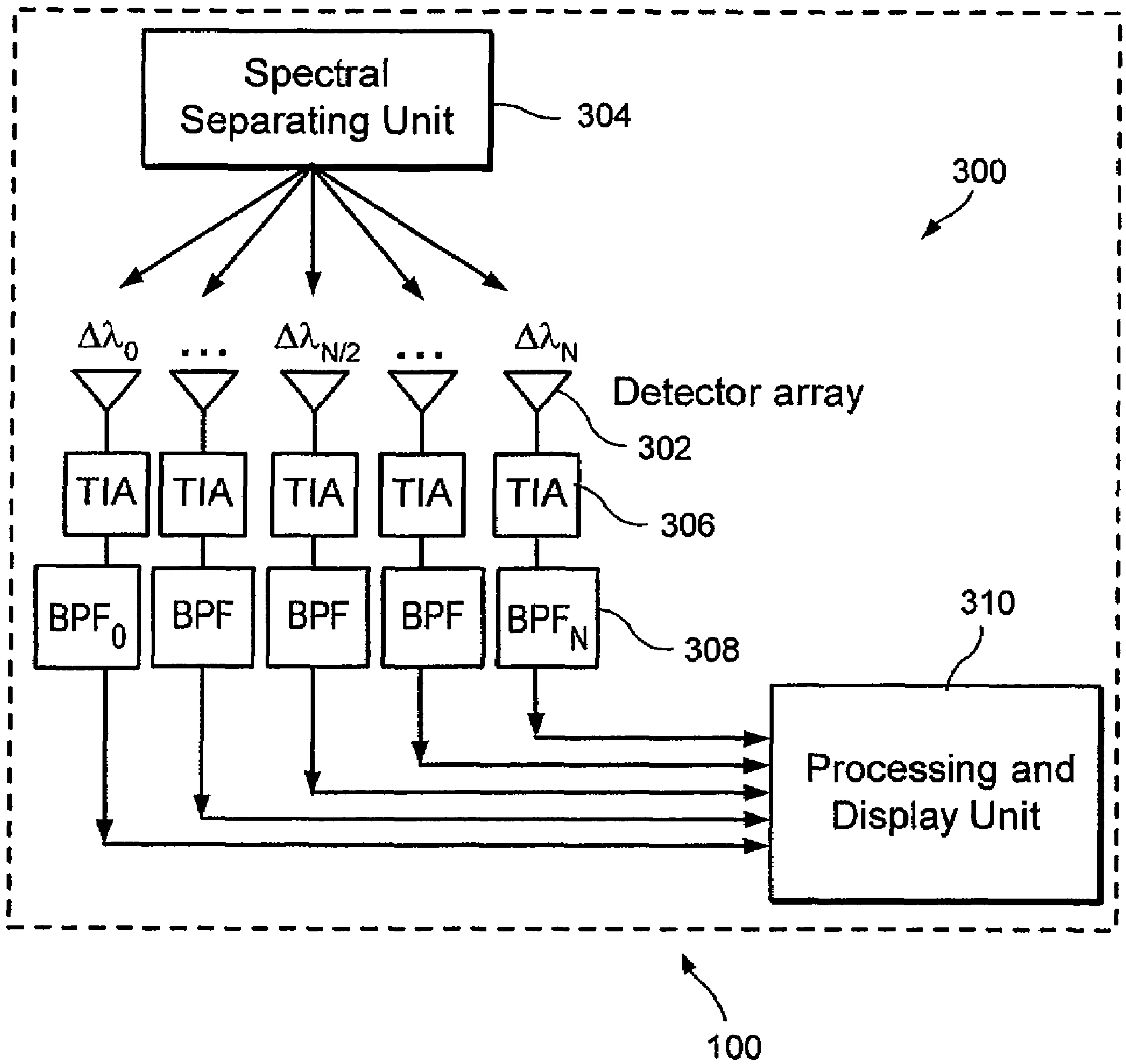

260
262
264
266

F I G. 4



Phase Tracker
102
108
104
Splitting unit
106
130
Low-Coherence Source
Sample arm
Tissue
110
Spectral Separating Unit
112
Δλ0 ... ΔλN/2 ... ΔλN
114
CCD Detector array 1
115
CCD Detector array 1
Processing and Display Unit
122

F I G. 5


Spectral Separating Unit
304
300
Δλ0
...
ΔλN/2
...
ΔλN
Detector array
302
TIA
TIA
TIA
TIA
TIA
306
BPF0
BPF
BPF
BPF
BPFN
308
310
Processing and Display Unit
100

F I G. 6

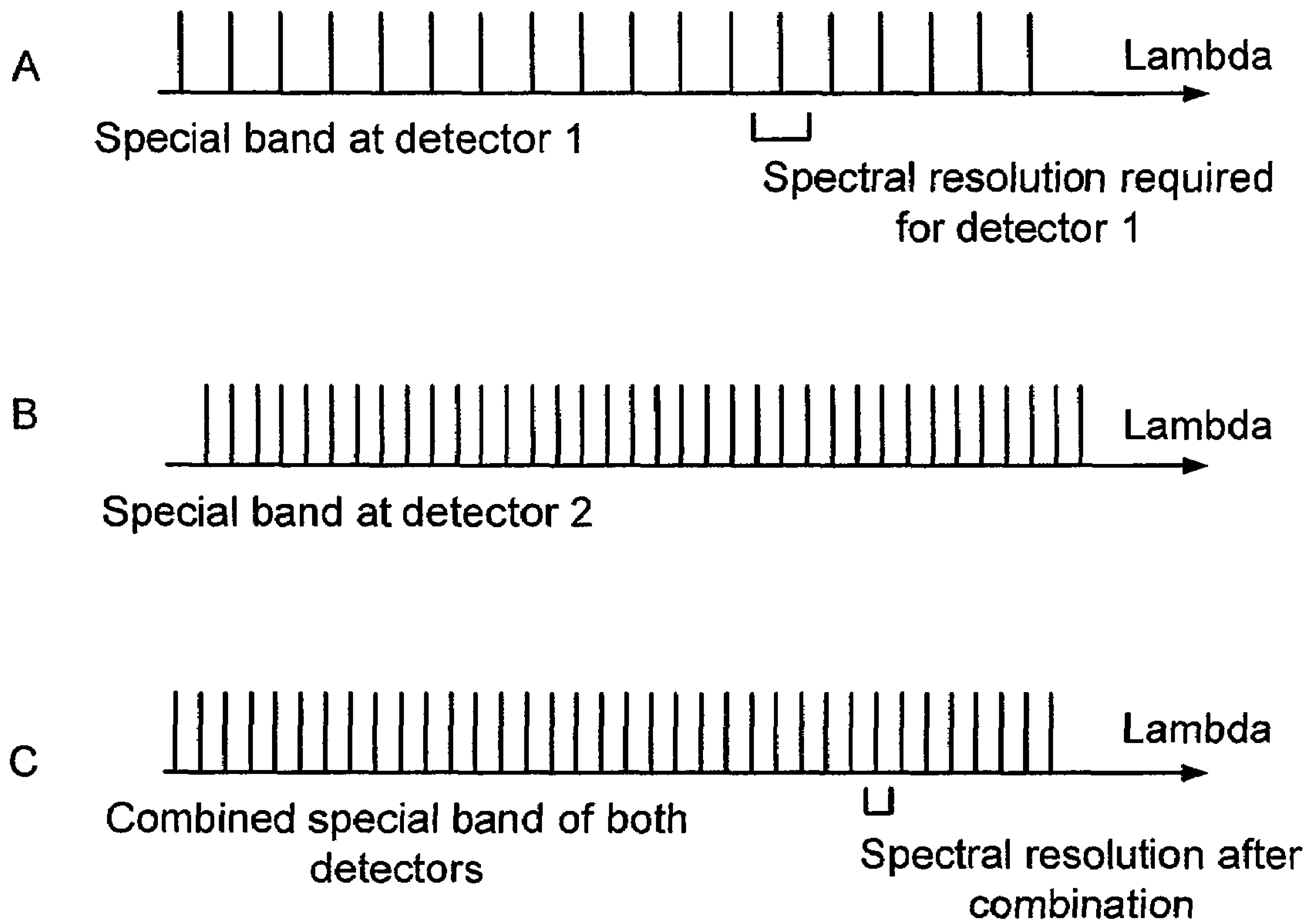

A
Lambda
Special band at detector 1
Spectral resolution required for detector 1
B
Lambda
Special band at detector 2
C
Lambda
Combined special band of both detectors
Spectral resolution after combination

FIG. 7

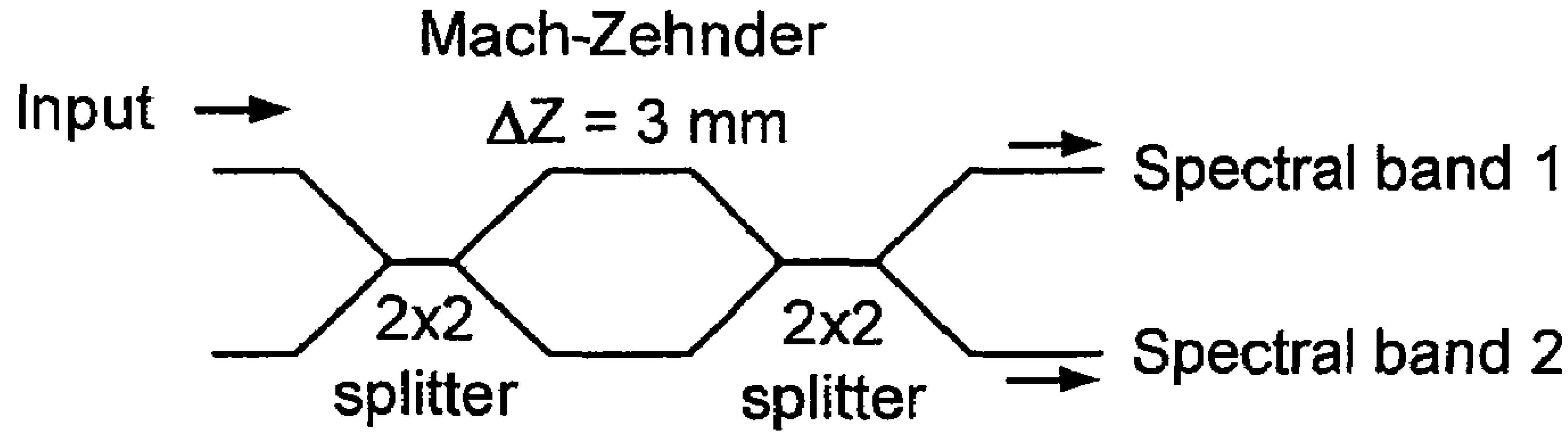

Mach-Zehnder
ΔZ = 3 mm
Input
Spectral band 1
Spectral band 2
2x2 splitter
2x2 splitter

FIG. 8

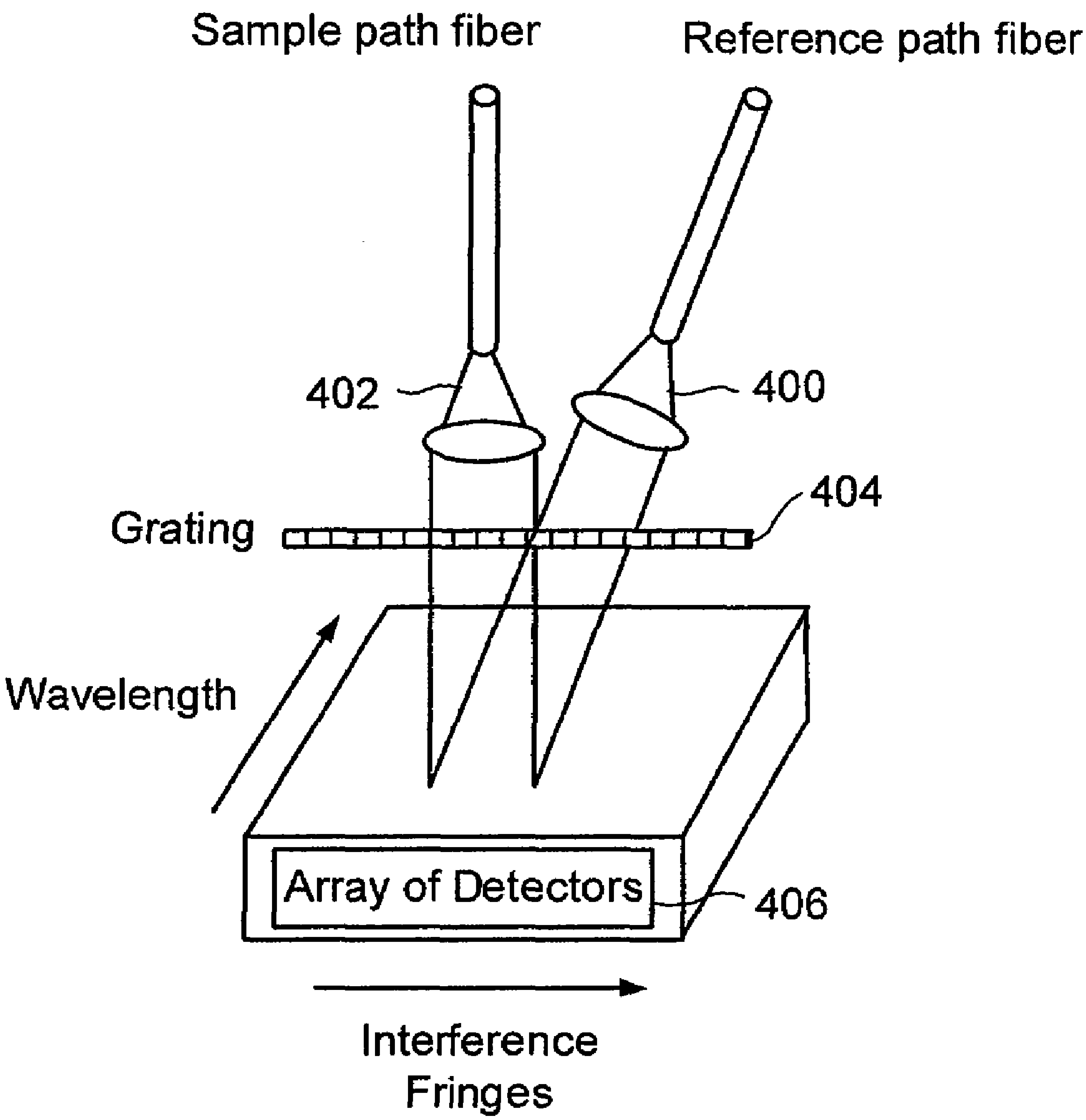

Sample path fiber
Reference path fiber
402
400
404
Grating
Wavelength
Array of Detectors
406
Interference
Fringes

FIG. 9

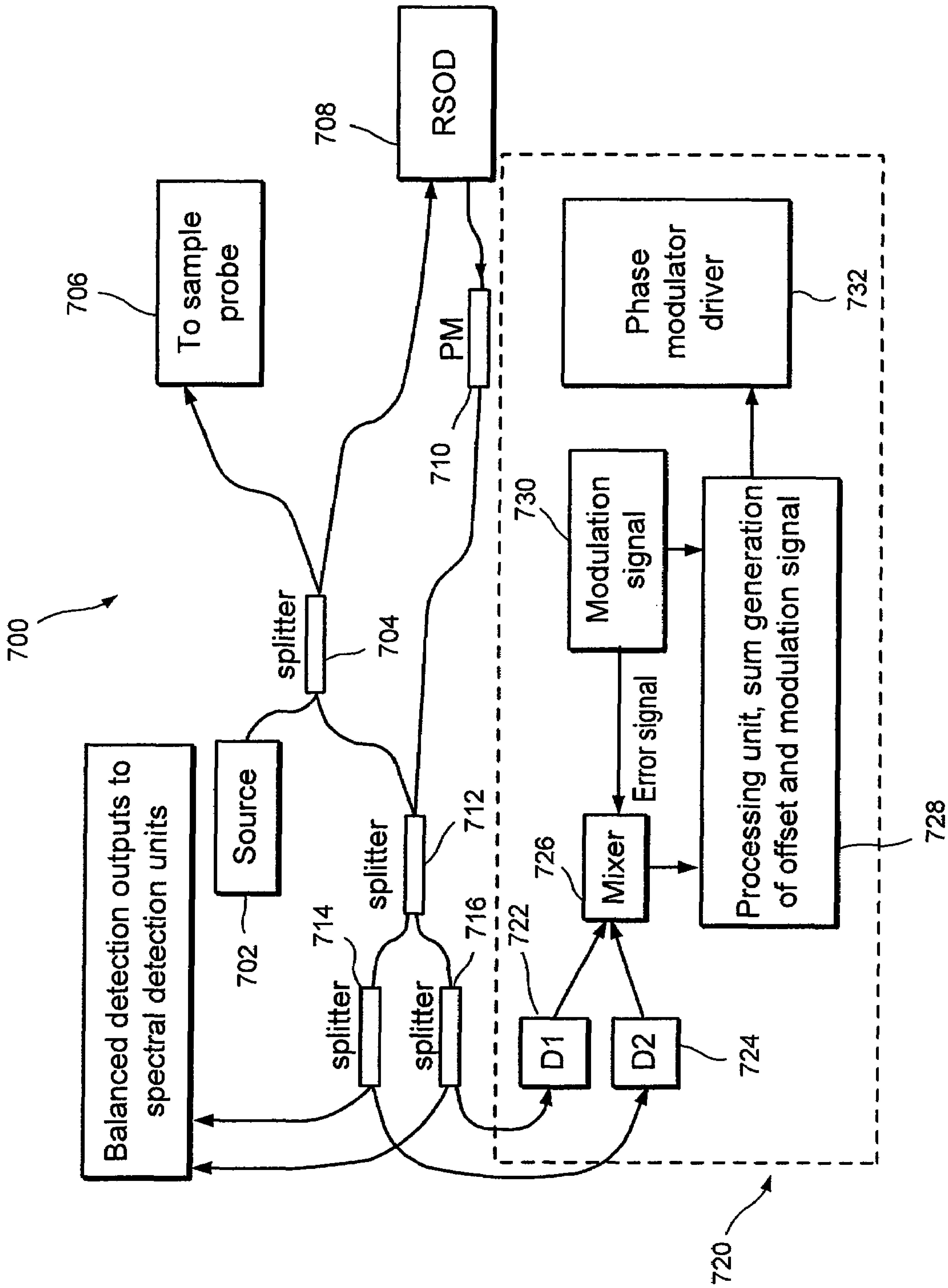

700
Balanced detection outputs to spectral detection units
Source
702
splitter
704
To sample probe
706
RSOD
708
PM
710
splitter
712
splitter
714
splitter
716
D1
722
D2
724
Mixer
726
Error signal
Modulation signal
730
Processing unit, sum generation of offset and modulation signal
728
Phase modulator driver
732
720

FIG. 10

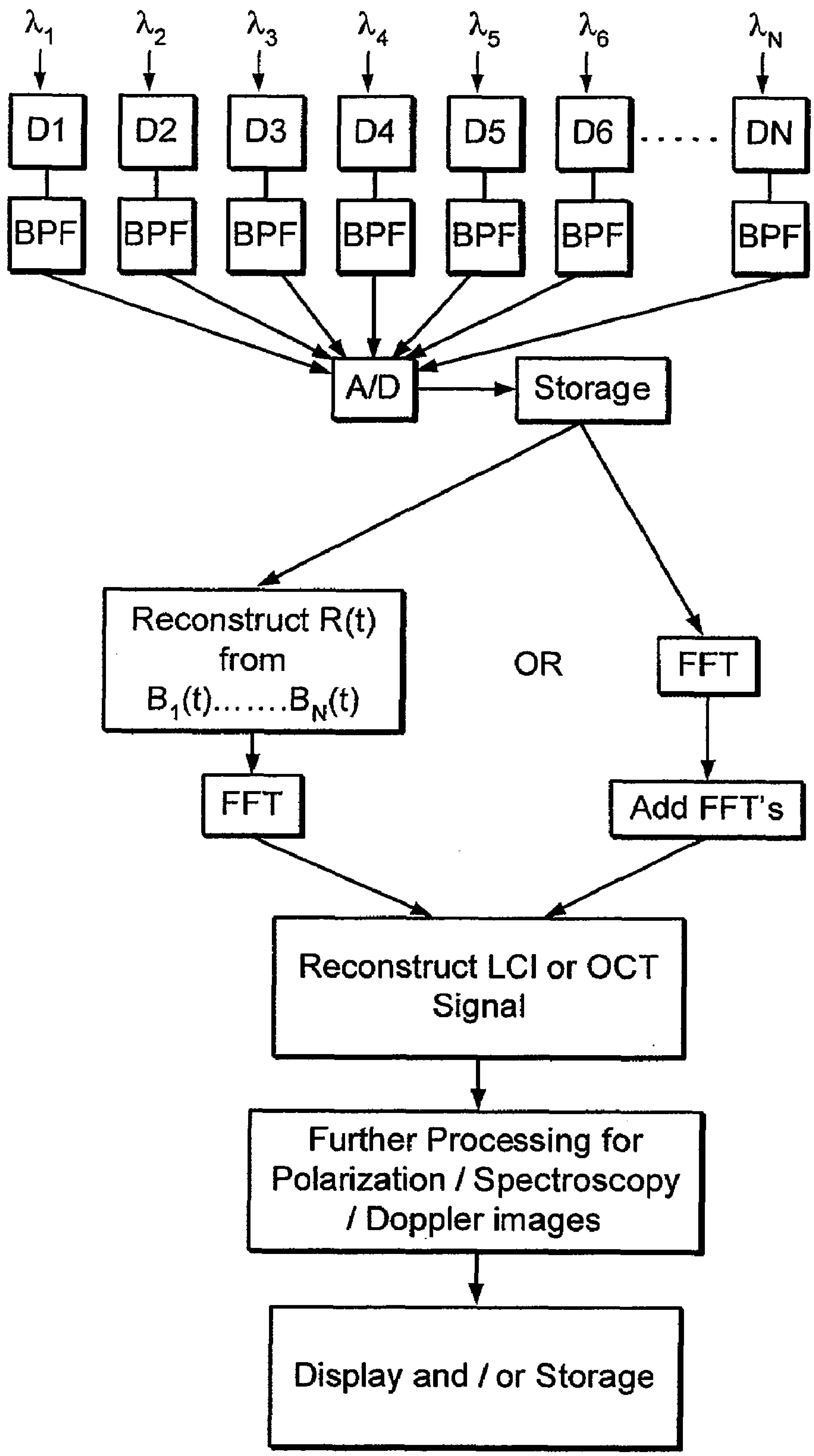

λ1
λ2
λ3
λ4
λ5
λ6
λN
D1
D2
D3
D4
D5
D6
DN
BPF
A/D
Storage
Reconstruct R(t) from B1(t).......BN(t)
OR
FFT
FFT
Add FFT's
Reconstruct LCI or OCT Signal
Further Processing for Polarization / Spectroscopy / Doppler images
Display and / or Storage

FIG. 11

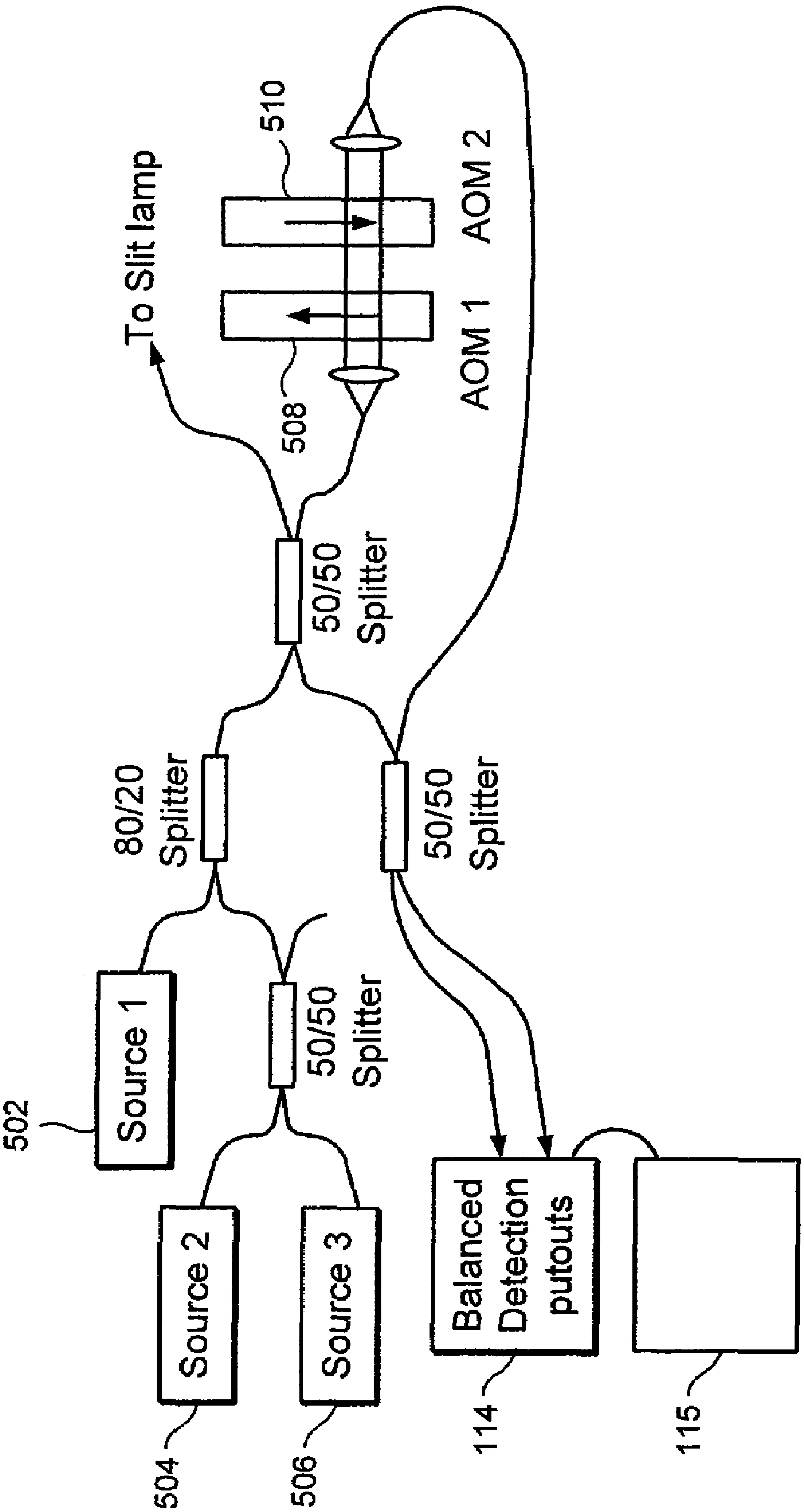

To Slit lamp
510
AOM 2
AOM 1
508
50/50 Splitter
80/20 Splitter
50/50 Splitter
Source 1
502
50/50 Splitter
Source 2
Source 3
504
506
Balanced Detection putouts
114
115

FIG. 12

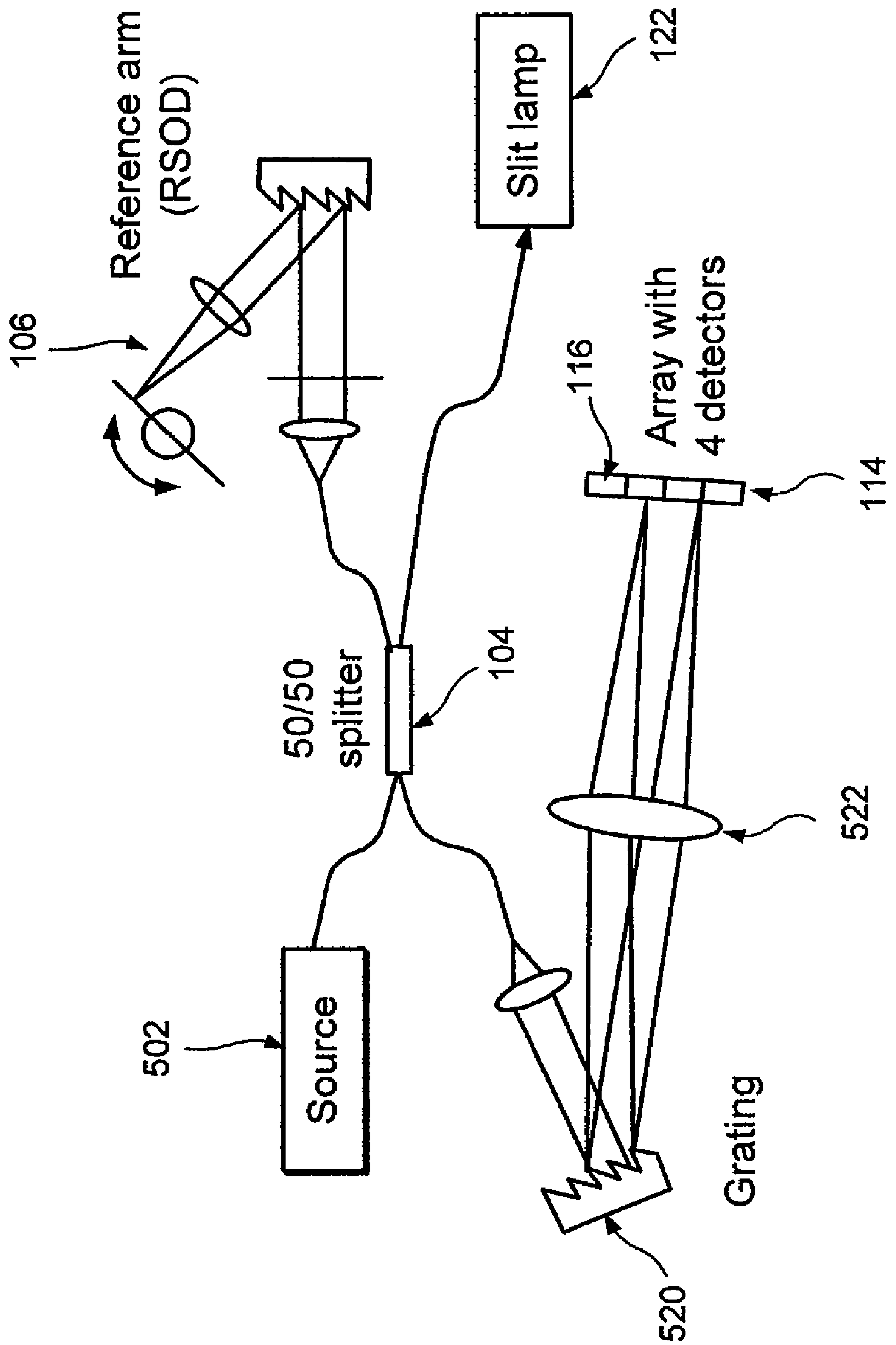
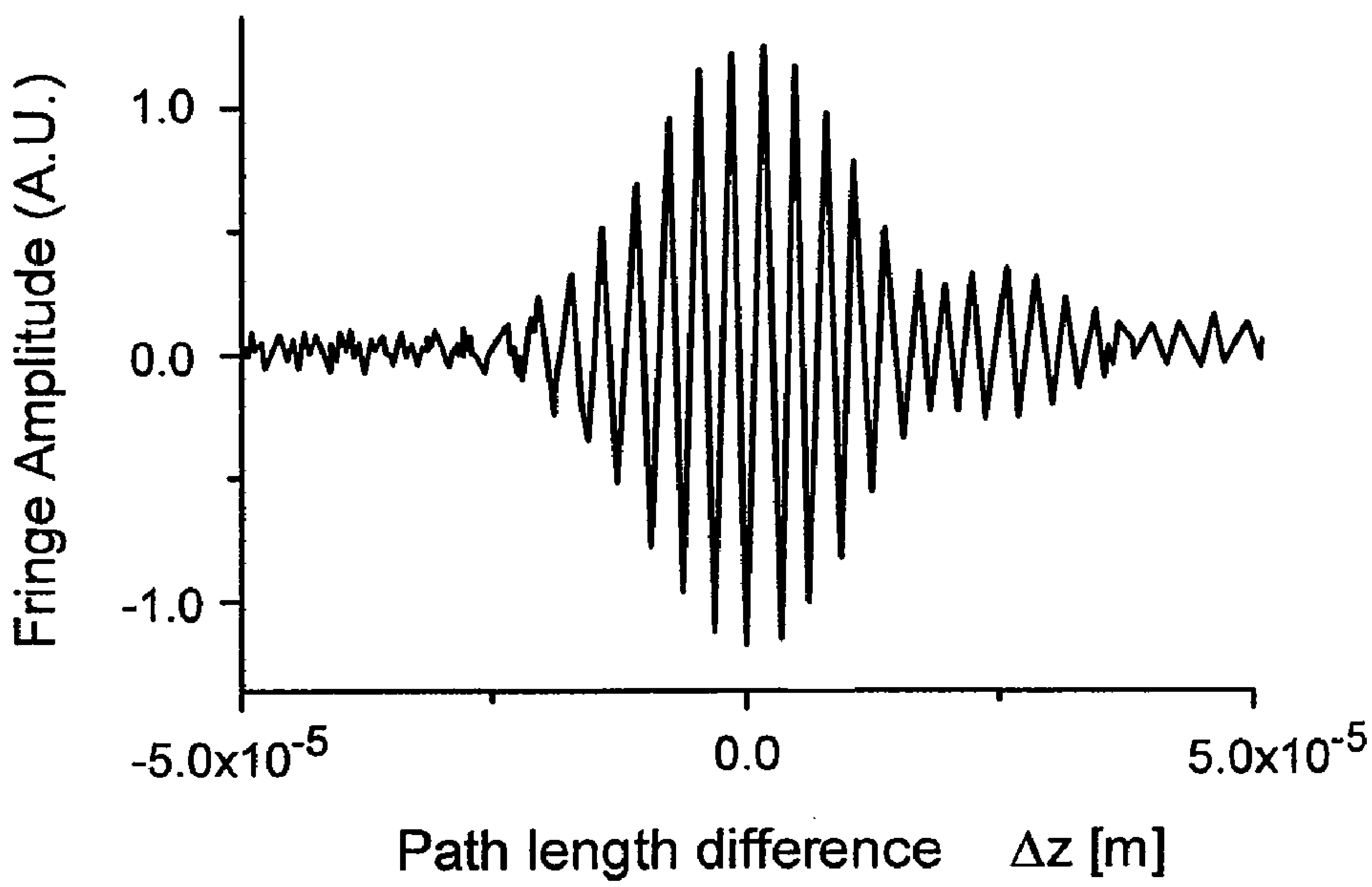

Reference arm
(RSOD)
106
Slit lamp
122
116
Array with
4 detectors
114
50/50
splitter
104
522
Source
502
Grating
520

FIG. 13


1.0
0.0
-1.0
Fringe Amplitude (A.U.)
-5.0x10-5
0.0
5.0x10-5
Path length difference Δz [m]

F I G. 14

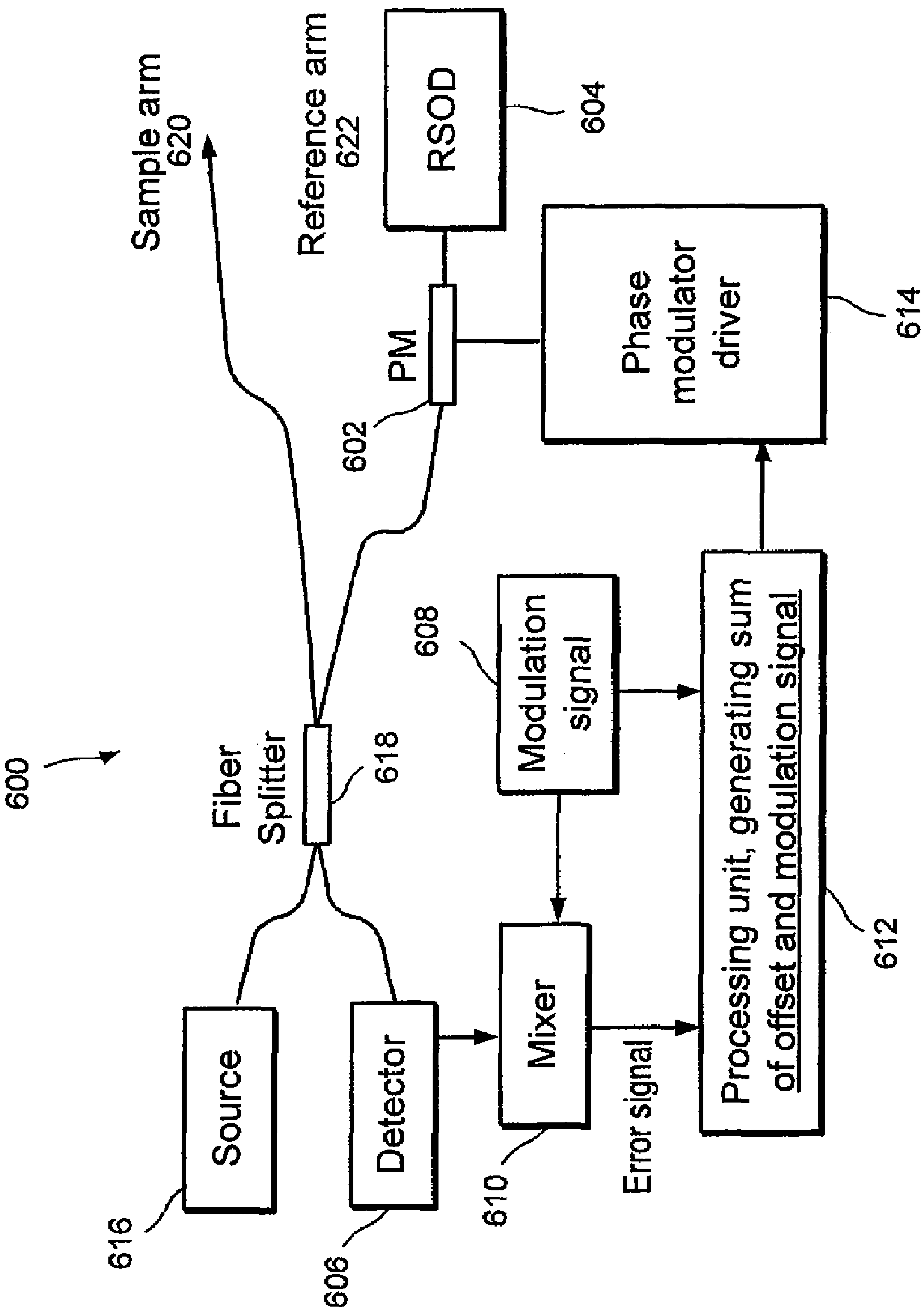
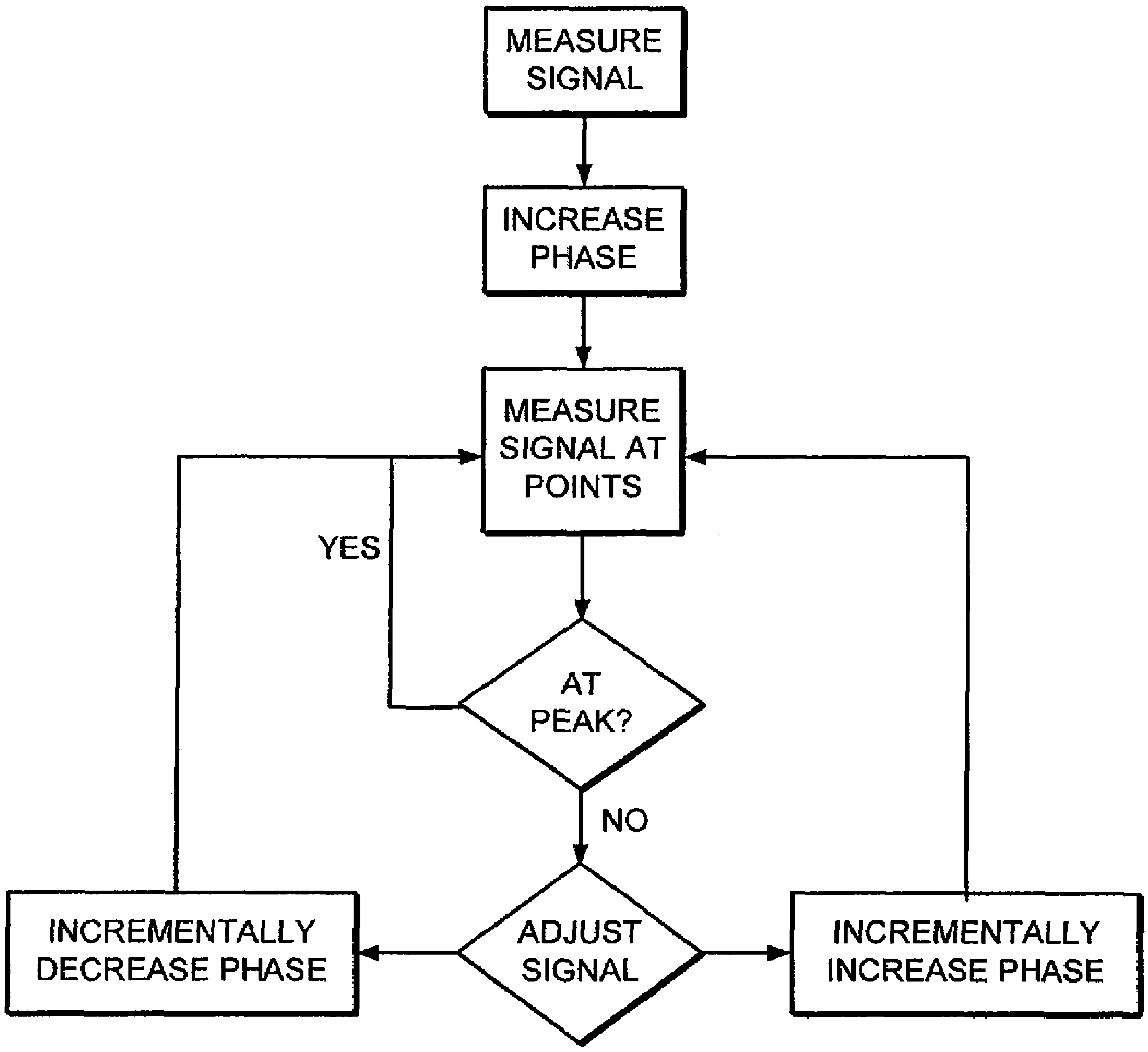
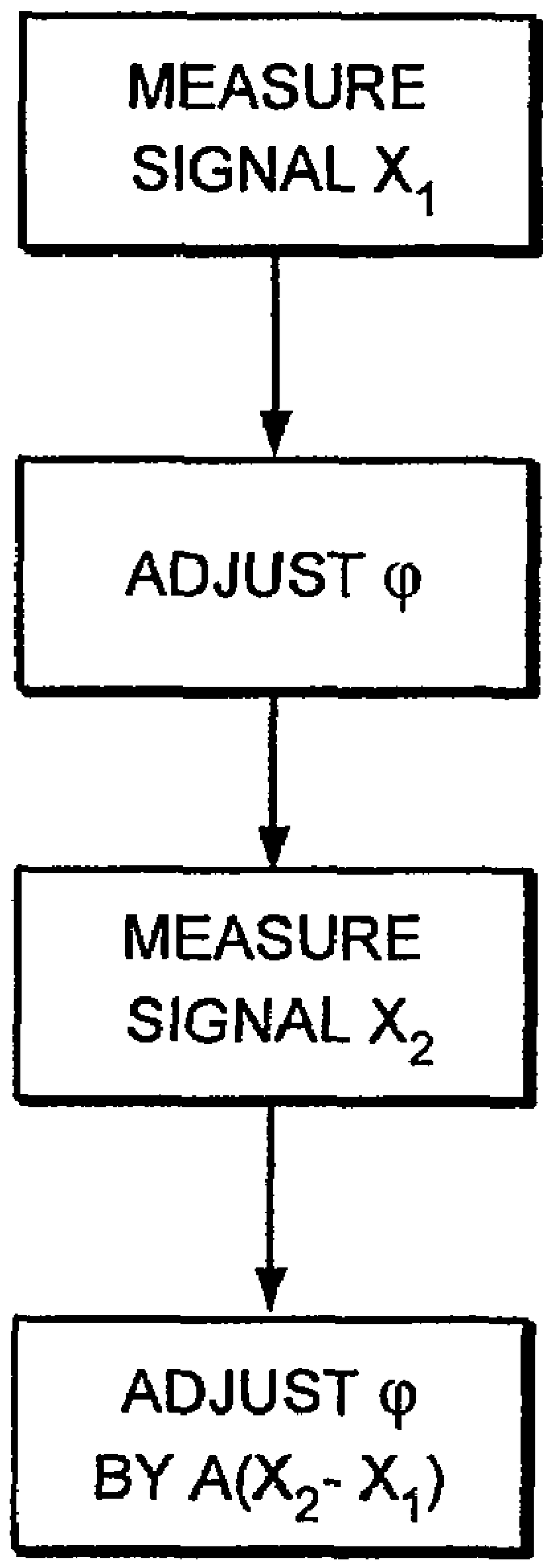

600
Sample arm
620
Reference arm
622
RSOD
604
PM
602
Phase
modulator
driver
614
Fiber
Splitter
618
Modulation
signal
608
Processing unit, generating sum
of offset and modulation signal
612
Source
616
Detector
606
Mixer
610
Error signal

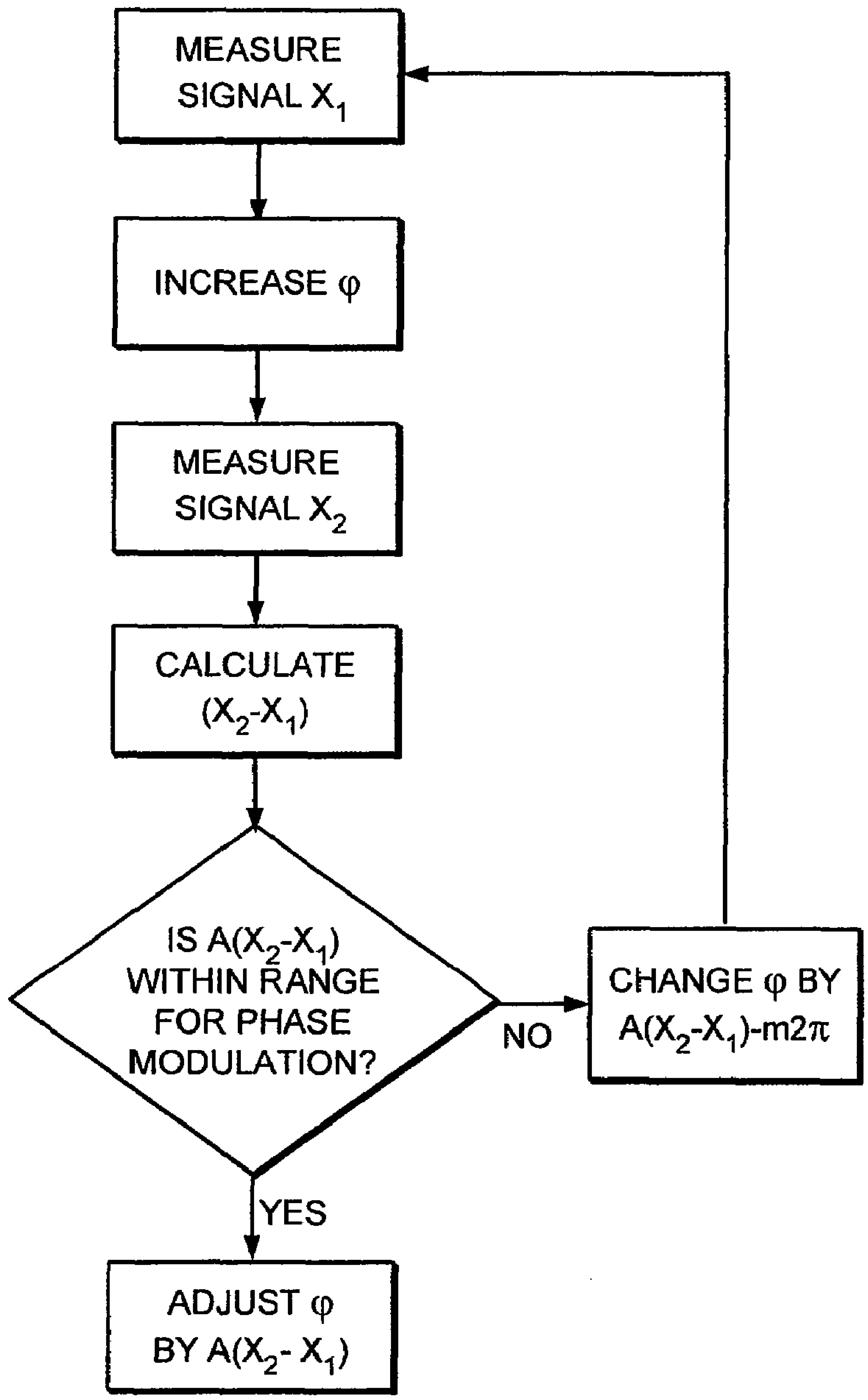
FIG. 15


MEASURE SIGNAL
INCREASE PHASE
MEASURE SIGNAL AT POINTS
YES
AT PEAK?
NO
ADJUST SIGNAL
INCREMENTALLY DECREASE PHASE
INCREMENTALLY INCREASE PHASE

F I G. 15A



F I G. 15B



F I G. 15C

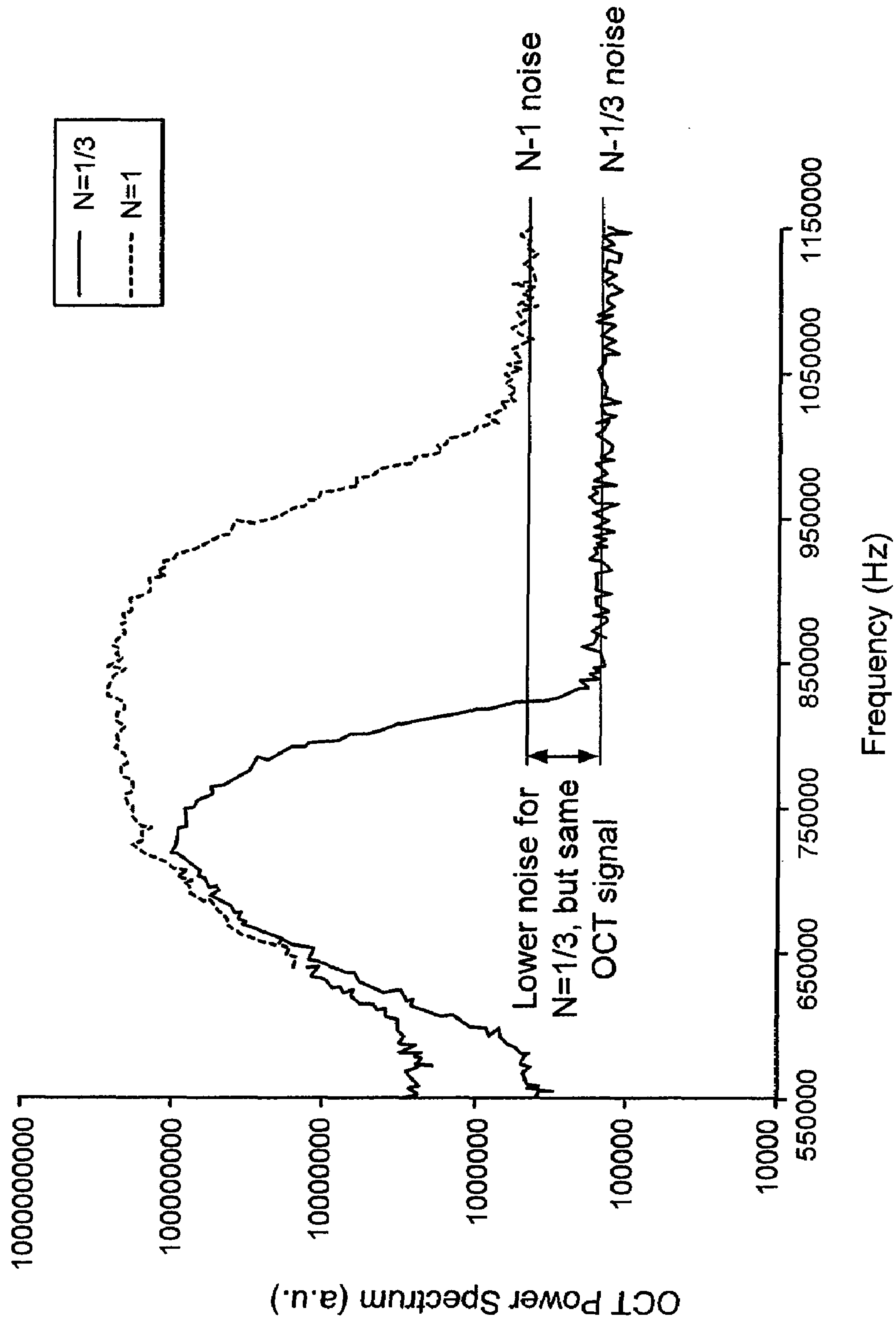
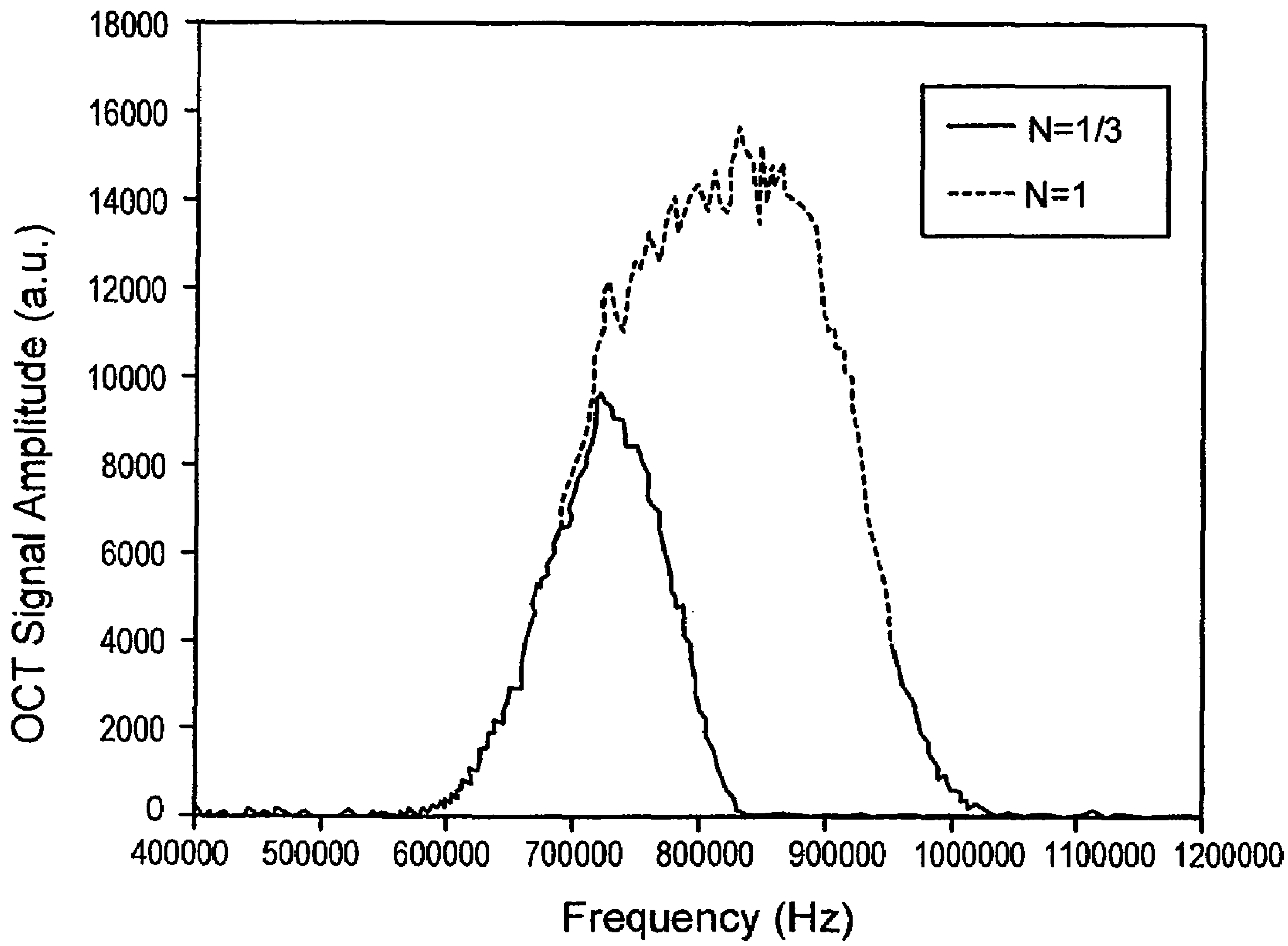
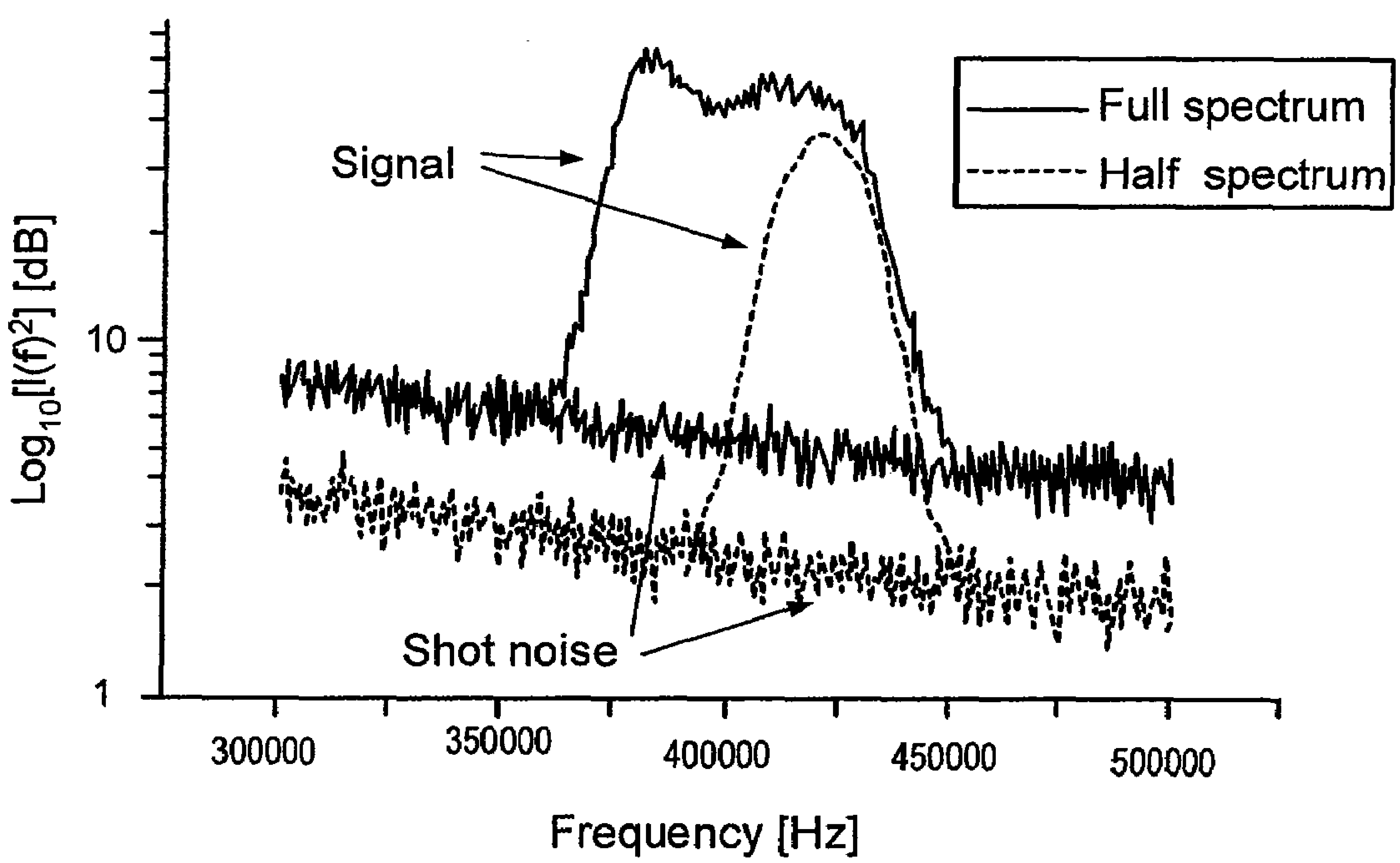

N=1/3
N=1
N-1 noise
N-1/3 noise
Lower noise for
N=1/3, but same
OCT signal
1000000000
100000000
10000000
1000000
100000
10000
550000
650000
750000
850000
950000
1050000
1150000
Frequency (Hz)
OCT Power Spectrum (a.u.)

FIG. 16



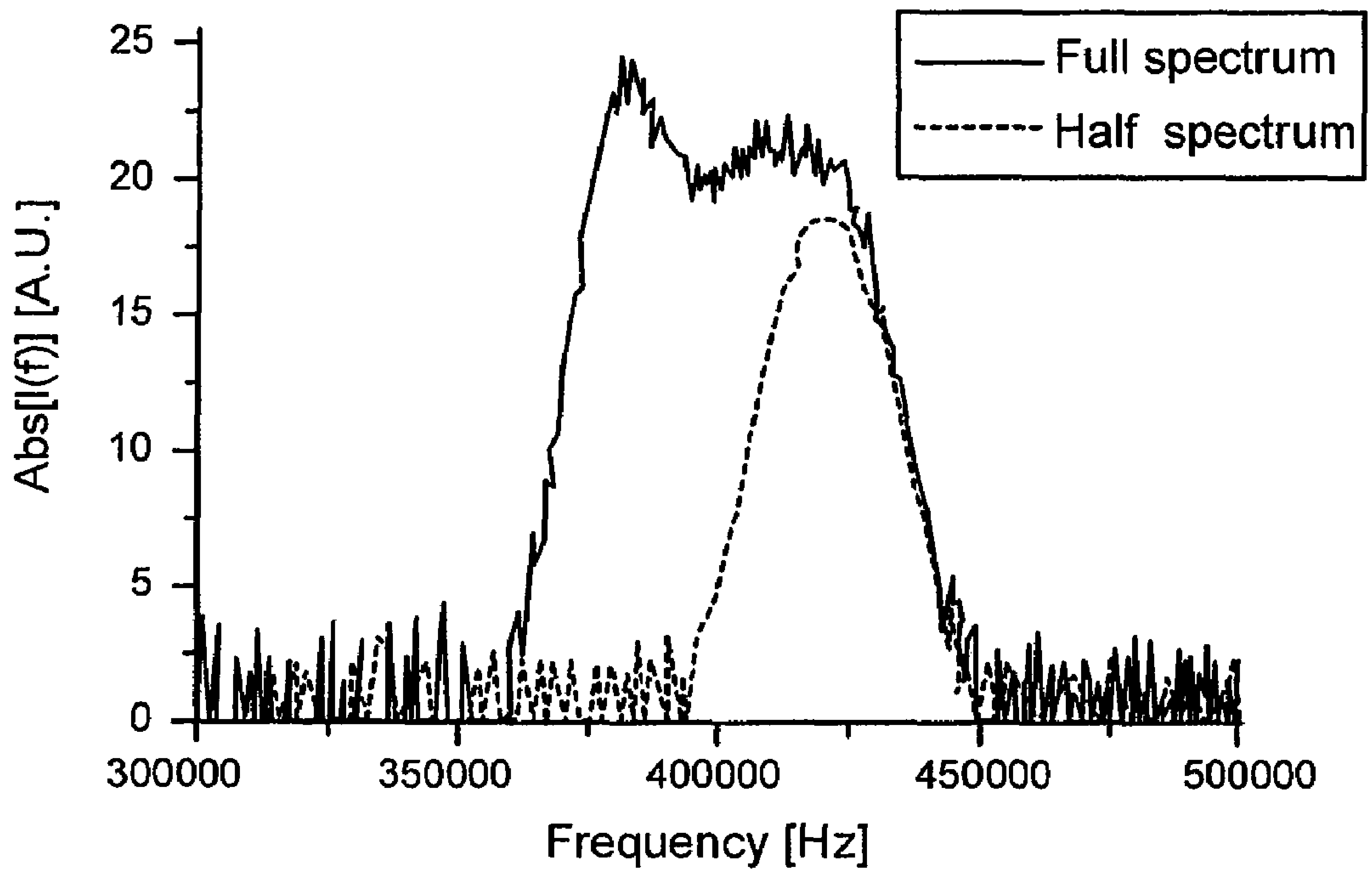
OCT Signal Amplitude (a.u.)
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
400000
500000
600000
700000
800000
900000
1000000
1100000
1200000
Frequency (Hz)
N=1/3
N=1

F I G. 17

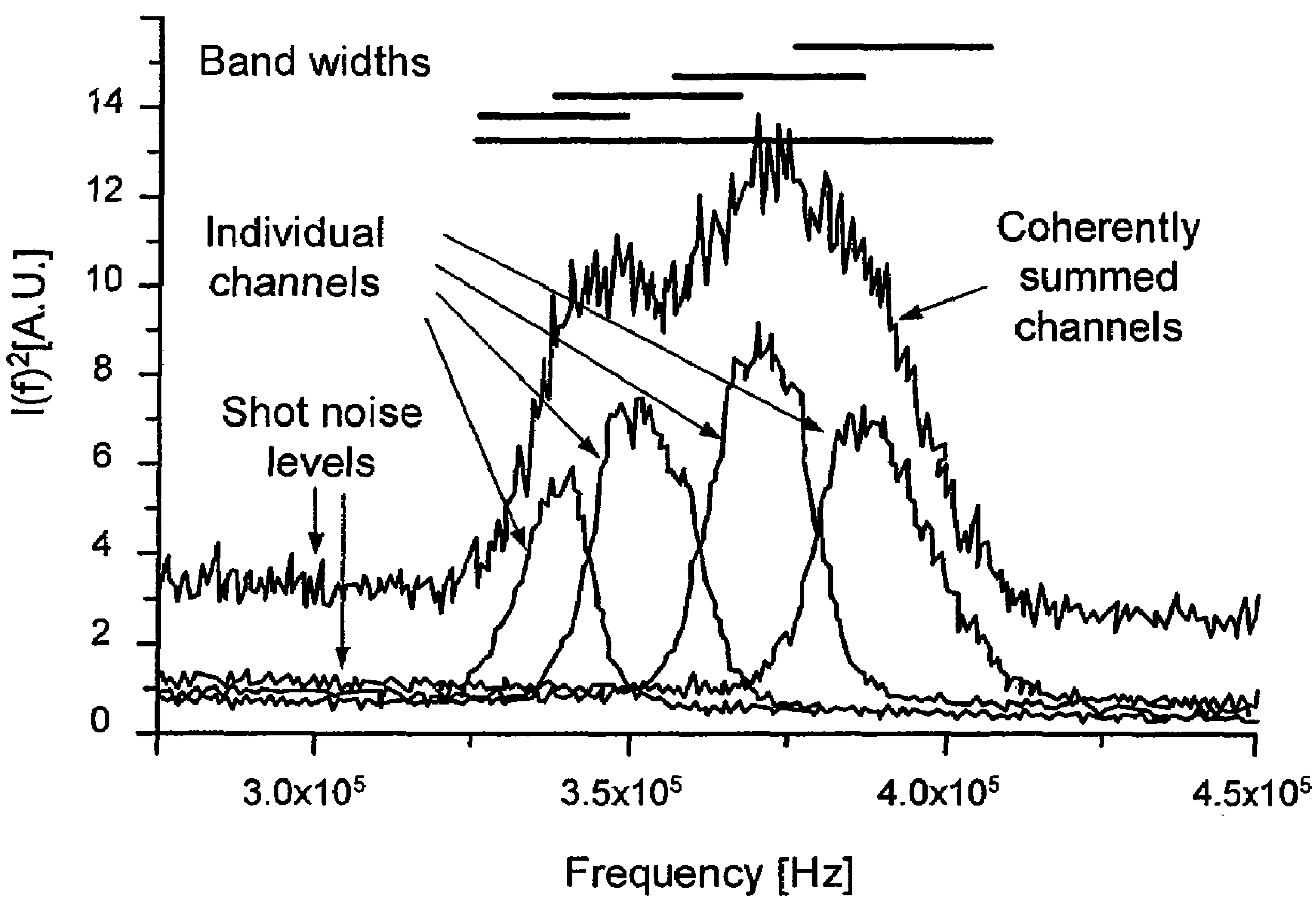


Log10[I(f)2] [dB]
10
1
300000
350000
400000
450000
500000
Frequency [Hz]
Full spectrum
Half spectrum
Signal
Shot noise

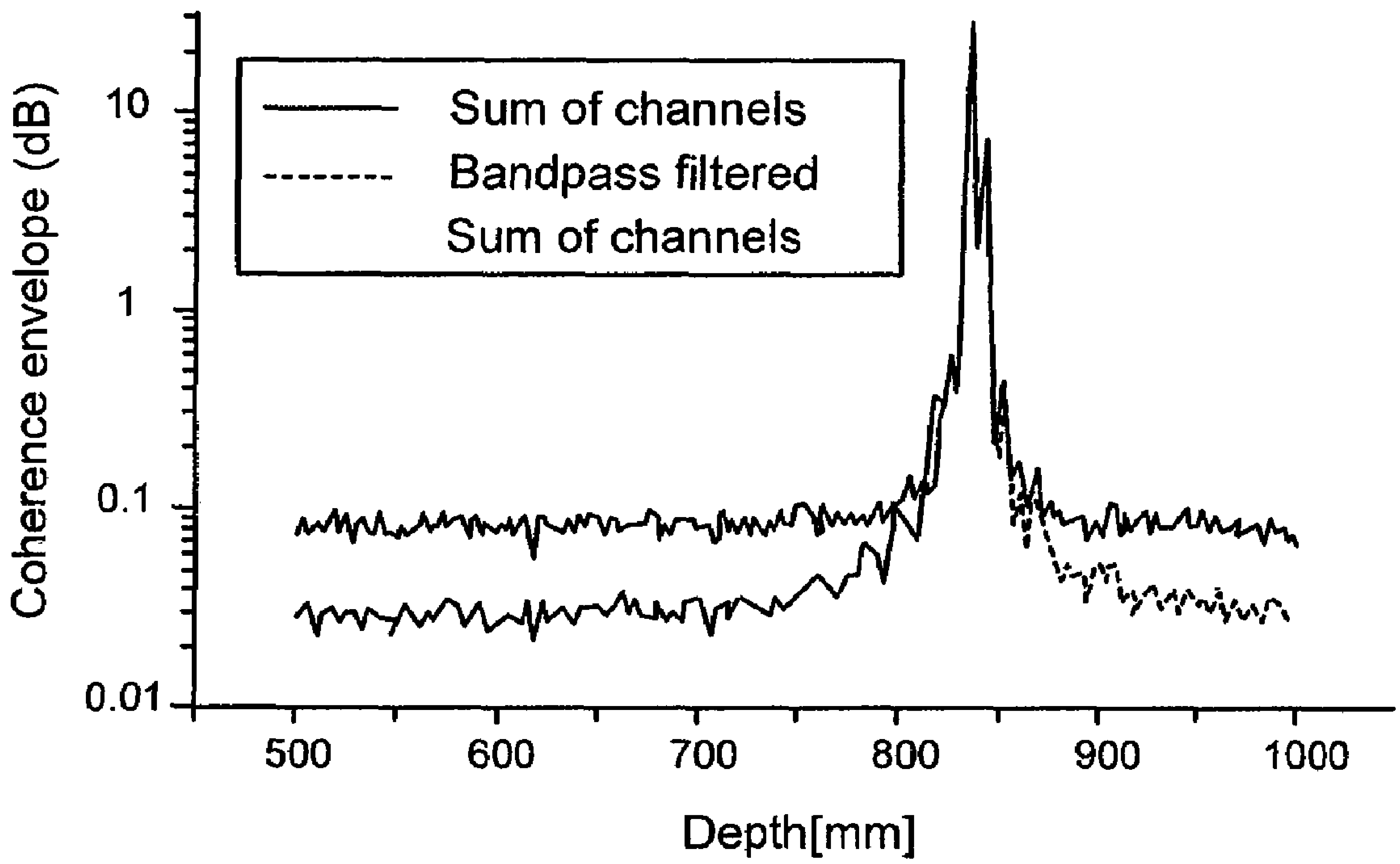
F I G. 18


Full spectrum
Half spectrum
25
20
15
10
5
0
Abs[I(f)] [A.U.]
300000
350000
400000
450000
500000
Frequency [Hz]

F I G. 19


Band widths
14
12
10
8
6
4
2
0
I(f)²[A.U.]
Individual channels
Coherently summed channels
Shot noise levels
3.0x10⁵
3.5x10⁵
4.0x10⁵
4.5x10⁵
Frequency [Hz]

F I G. 20


Sum of channels
Bandpass filtered
Sum of channels
Coherence envelope (dB)
10
1
0.1
0.01
500
600
700
800
900
1000
Depth[mm]

F I G. 21

APPARATUS AND METHOD FOR RANGING AND NOISE REDUCTION OF LOW COHERENCE INTERFEROMETRY LCI AND OPTICAL COHERENCE TOMOGRAPHY OCT SIGNALS BY PARALLEL DETECTION OF SPECTRAL BANDS

CROSS-REFERENCE TO RELATED APPLICATIONS

The present application is a divisional of U.S. patent application Ser. No. 10/501,276, filed Jul. 9, 2004, now U.S. Pat No. 7,355,716 which is U.S. National Phase of International Application No. PCT/US03/02349 filed Jan. 24, 2003. This application also claims benefit of U.S. provisional patent application No. 60/351,904, filed Jan. 24, 2002, entitled APPARATUS AND METHOD FOR RANGING AND SHOT NOISE REDUCTION OF LOW COHERENCE INTERFEROMETRY (LCI) AND OPTICAL COHERENCE TOMOGRAPHY (OCT) SIGNALS BY PARALLEL DETECTION OF SPECTRAL BANDS, and copending U.S. application Ser. No. 10/136,813, filed Apr. 30, 2002, entitled METHOD AND APPARATUS FOR IMPROVING IMAGE CLARITY AND SENSITIVITY IN OPTICAL COHERENCE TOMOGRAPHY USING DYNAMIC FEEDBACK TO CONTROL FOCAL PROPERTIES AND COHERENCE GATING, both commonly assigned to the assignee of the present application. The disclosures of all these applications are incorporated herein by reference in their entireties.

FIELD OF THE INVENTION

The present invention relates to apparatus and a method for dramatically increasing the sensitivity in the detection of optical coherence tomography and low coherence interferometry signals by detecting a parallel set of spectral bands, each band being a unique combination of optical frequencies.

BACKGROUND OF THE ART

Two methods currently exist to implement depth ranging in turbid media. The first method is known as Low Coherence Interferometry ("LCI"). This method uses a scanning system to vary the reference arm length and acquire the interference signal at a detector and demodulating the fringe pattern to obtain the coherence envelope of the source cross correlation function. Optical coherence tomography ("OCT") is a means for obtaining a two-dimensional image using LCI. OCT is described by Huang et al. in U.S. Pat. No. 5,321,501. Multiple variations on OCT have been patented, but, many suffer from less than optimal signal to noise ratio ("SNR"), resulting in non-optimal resolution, low imaging frame rates, and poor depth of penetration.

A second method for depth ranging in turbid media is known in the literature as spectral radar. In spectral radar the real part of the cross spectral density of sample and reference arm light is measured with a spectrometer. Depth profile information is encoded on the cross-spectral density modulation. Prior art for spectral radar is primarily found in the literature. U.S. Pat. No. 5,491,552 discloses a spectral radar invention which employs a variation of this technique. The use of spectral radar concepts to increase the signal to noise ratio of LCI and OCT have been described earlier. However, in this description, only the real part of the complex spectral density is measured and the method requires a large number of detector elements (~2,000) to reach scan ranges on the order of a millimeter. It would be desirable to have a method that would allow for an arbitrary number of detector elements. Secondly, the previously described method uses a charge coupled device ("CCD") to acquire the data, which requires a reduction of the reference arm power to approximately the same level as the sample arm power. As a result, large integration times are needed to achieve the SNR improvement. Since no carrier is generated, the 1/f noise will dominate the noise in this system. Power usage is a factor in such imaging techniques. For example in ophthalmic uses, only a certain number of milliwatts of power is tolerable before thermal damage can occur. Thus, boosting power is not feasible to increase SNR in such environments. It would be desirable to have a method of raising the SNR without appreciably increasing power requirements.

SUMMARY OF THE INVENTION

The present invention increases the SNR of LCI and OCT by splitting the LCI broad bandwidth source into N spectral bands. The N spectral bands are individually detected and processed to provide an increase in the SNR by a factor of N. This increase in SNR enables LCI or OCT imaging by a factor of N times faster, or alternatively allows imaging at the same speed with a source that has N times lower power. As a result, the present invention overcomes two of the most important shortcomings of LCI and OCT, i.e., source availability and scan speed. The factor N may reach more than 1,000, and allows construction of OCT and LCI systems that can be more than three orders of magnitude improved from OCT and LCI technology currently in practice.

The present invention enables a breakthrough in current data acquisition speeds and availability of sources for OCT. The shot noise reduction allows for much lower source powers, or much higher acquisition rates than current systems. Limitations in current data acquisition rates (approximately 4 frames/sec) are imposed by available source power. An increase in the sensitivity of the detection by a factor of 8 would allow real time imaging at a speed of 30 frames per second. An increase of the sensitivity by a factor of 1,000-2,000 would allow for the use of sources with much lower powers and higher spectral bandwidths which are readily available, cheaper to produce, and can generate broader bandwidths.

For ophthalmic applications of OCT, the efficient detection would allow for a significant increase of acquisition speed. The limitation in ophthalmic applications is the power that is allowed to enter the eye according to the ANSI standards (approximately 700 microwatts at 830 nm). Current data acquisition speed in ophthalmic applications is approximately 100-500 A-lines per second. The power efficient detection would allow for A-line acquisition rates on the order of 100,000 A-lines per second, or video rate imaging at 3,000 A-lines per image.

In summary, the present invention represents a greatly improved means for performing LCI and OCT, and as a result, would be of great interest to entities considering developing LCI and OCT diagnostic technologies for medical and non-medical applications.

Other features and advantages of the present invention will become apparent upon reading the following detailed description of embodiments of the invention, when taken in conjunction with the appended claims.

BRIEF DESCRIPTION OF THE DRAWINGS

The invention is illustrated in the drawings in which like reference characters designate the same or similar parts throughout the figures of which:

FIG. **1** is a schematic view of a preferred embodiment of the parallel detection scheme for LCI.

FIG. **2** is a schematic view of a preferred embodiment of a standalone system

FIG. **3** is a schematic view showing spectral demultiplexing into 2 bands.

FIG. **4** is a schematic of spectral demultiplexing into 4 bands. The spectral resolution required for each detector is twice as course as in the case of multiplexing into 2 bands.

FIG. **5** is a graph of frequency versus OCT power spectrum.

FIG. **6** is a graph of frequency versus amplitude spectrum subtracted from the shot noise (experimental data) for the N=1 (dotted line) and N=⅓ (solid line) cases.

FIG. **7** is a flowchart depicting the reconstruction of LCI or OCT signal from wavelength bands.

FIG. **8** is a schematic view of demultiplexing unit in combination with two integrating CCD arrays for detection of the dual-balanced wavelength demultiplexed signal.

FIG. **9** is a schematic view of using beam recombination to provide one dimension of interference information along one dimension of a two-dimensional detector array, while performing wavelength demultiplexing along the other dimension of the two dimensional array.

FIG. **10** is a schematic view of a phase tracking system according to one embodiment of the present invention.

FIG. **11** is a flowchart depicting the reconstruction of LCI or OCT signal from wavelength bands.

FIG. **12** is a schematic view of a spectral domain OCT interferometer design with a source combining the spectra of several superluminescent sources.

FIG. **13** is a schematic view of a system with a four detector array.

FIG. **14** is a graph of a typical interference patter as a function of path length difference between sample arm and reference arm.

FIG. **15** is an embodiment of a phase tracker system with an extended phase lock range.

FIGS. **15**A-C are flow diagrams of a method.

FIG. **16** is a graph of frequency versus OCT power spectrum.

FIG. **17** is a graph of frequency versus amplitude spectrum substracted from the shot noise (experimental data) for the N=1 (dotted line) and N=1/3 (solid line) cases.

FIG. **18** is a graph of power density for the full spectrum as a function of frequency.

FIG. **19** is a graph after subtraction of the shot noise levels.

FIG. **20** is a graph after processing the signals.

FIG. **21** is a graph of the coherence envelope for the coherently summed channels.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Background

The present invention describes a hybrid method that implements aspects of LCI and OCT where the reference arm is scanned, and spectral radar, which does not require reference arm scanning. The signal in the detection arm of an OCT system is split into more than one spectral band before detection. Each spectral band is detected by a separate photo detector and amplified. For each spectral band the signal is band pass filtered around the signal band by analog electronics and digitized, or, alternatively, the signal may be digitized and band pass filtered in software. As a consequence, the shot noise contribution to the signal is reduced by a factor equal to the number of spectral bands. The signal remains the same. The reduction of the shot noise increases the dynamic range and sensitivity of the system. In the limit of many detectors, no ranging or reference arm scanning is required and the method is similar to spectral radar except that phase information of the cross spectral density is preserved.

Theory

In current OCT system, the recombined light of sample and reference arm is detected by a single detector. The signal is determined by the interference of light reflected from sample and reference arm. For a single object in the sample arm, the OCT signal is proportional to the real part of the Fourier transform of the source spectrum S(k),

$$R(\Delta z) \propto \mathrm{Re}\int \exp(ik\Delta z)S(k)dk, \tag{1}$$

with $k=2\pi/\lambda=\omega/c$ the free space wave number and $\Delta z=z-z'$ the path length difference between reference and sample waves respectively. R(z) is the interference part of the signal detected at the photo detectors. The intensity I(z) backscattered from the sample arm at location z is proportional to the square of the envelope of R(z), $I(z)\propto R^2(z)$.

Converting path length difference Δz to time difference τ between arrival of reference and sample waves, $\tau=\Delta z/c$ and using that the time difference τ is given by measurement time t times twice the speed of the reference mirror v divided by the speed of light c, $\tau=2vt/c$, we obtain,

$$R(t) \propto \mathrm{Re}\int \exp(i\omega tv/c)S(\omega)d\omega, \tag{2}$$

with t the measurement time.

Fourier transforming the depth profile R(t), the frequency spectrum of the signal is obtained,

$$|R(\omega)|\propto|S(\omega c/v)|, \tag{3}$$

This demonstrates that each angular frequency of the light source or equivalently each wavelength of the source is represented at its own frequency in the measured interferometric signal. The depth profile information R(t) can be obtained from the complex cross spectral density $R(\omega)$ by a Fourier transform.

The complex cross spectral density can also be obtained by splitting the signal R(t) in several spectral bands by means of a dispersive or interferometric element. At each detector, only part of the complex cross spectral density is determined. Combining the cross spectral densities of each detector, the full spectral density of the signal is retrieved.

Thus, the same information can be obtained by separating spectral components to individual detectors. Combining the signal of all detectors in software or hardware would result in the same signal as obtained with a single detector. However, a careful analysis of the noise present at each frequency in the case of many individual detectors, reveals that the shot noise contribution is significantly lower, leading to a significant signal to noise improvement. The signal to noise improvement is linearly dependent on the number of spectral bands in which the signal is split. Thus, two spectral bands give a signal to noise improvement of a factor of 2, four spectral bands give a signal to noise improvement of a factor of 4, etc.

Signal to Noise Analysis of Optical Coherence Tomography Signals in the Frequency Domain

For a single reflector in the sample arm, the interference fringe signal as a function of position is given by

$$R(\Delta z) \propto \mathrm{Re}\int \exp(ik\Delta z)S(k)dk,$$

or equivalently as a function of time,

$$R(t) \propto \mathrm{Re}\int \exp(i\omega tv/c)S(\omega)d\omega$$

The coherence envelope peak value is found by setting $\Delta z=0$ or $t=0$;

$$I_{peak} \propto \int S(k)dk \propto \int S(\omega)d\omega$$

In the frequency domain, the Fourier transform of R(t) is given by

$$R(\omega) = \int R(t)e^{i\omega t}dt = \int \mathrm{Re}\int \exp(i\omega' tv/c)S(\omega')d\omega' e^{i\omega t}dt = S(\omega c/v)$$

The peak value is given by

$$I_{peak} \propto \int R(\omega)d\omega = \int S(\omega c/2v)d\omega$$

In terms of electrical power, the signal is defined as I_{peak}^2. In the frequency domain, the signal is,

$$I_{peak}^2 \propto \left[\int R(\omega)d\omega\right]^2 = \left[\int S(\omega c/2v)d\omega\right]^2$$

or in terms of sample and reference arm power,

$$I_{peak}^2 \propto \left[\int \sqrt{S_{ref}(\omega c/2v)} * \sqrt{S_{sample}(\omega c/2v)}\, d\omega\right]^2 = a(z)\left[\int S_{ref}(\omega c/2v)d\omega\right]^2,$$

with $S_{sample}(\omega c/2v)=a(z)S_{ref}(\omega c/2v)$ and a(z) the reflectivity at z.

Thus, the signal is proportional to

$$a(z)\left[\int S_{ref}(\omega c/2v)d\omega\right]^2.$$

The total power P_{ref} is given by

$$P_{ref} = \int S_{ref}(\omega c/2v)d\omega$$

The shot noise has a white noise distribution and the shot noise density is proportional to the total power on the detector

$$N_{shot}(\omega) \propto \int S_{ref}(\omega c/2v)d\omega = P_{ref}$$

The shot noise density is given in units [W^2/Hz], [A^2/Hz] or [V^2/Hz]. The total shot noise that contributes to the noise is the Shot noise density multiplied with the bandwidth BW, $N_{shot}=P_{ref}*BW$

Using the above expressions for the Signal and Noise, the SNR ratio for a single detector is given by

$$SNR \propto a(z)\left[\int S_{ref}(\omega c/2v)d\omega\right]^2 / P_{ref} * BW = P_{sample}/BW.$$

For a two detector configuration, where the spectrum is equally split over two detectors, the bandwidth BW per detector is half, as is the reference power. For an individual detector in the two detector configuration the signal is given by an integration over half the signal bandwidth,

$$a(z)\left[\int_{0.5*BW} S_{ref}(\omega c/2v)d\omega\right]^2.$$

The noise is given by $0.5*P_{ref}*0.5*BW$ and the SNR is now

$$SNR \propto a(z)\left[\int_{0.5BW} S_{ref}(\omega c/2v)d\omega\right]^2 / 0.5P_{ref} * 0.5BW = P_{sample}/BW.$$

The SNR is the same as in the previous case where the full spectrum was detected by a single detector.

To evaluate the Signal to noise for two detectors simultaneously, the signals of both detectors are coherently added after digital or analog band pass filtering, i.e., after Fourier transforming of the signal R(t) the frequency components R(ω) within the signal band of each detector are added to form the total signal in the frequency domain. The signal is,

$$I_{peak}^2 \propto a(z)\left[\begin{array}{l}\int_{0.5BW} S_{ref}(\omega c/2v)d\omega + \\ \int_{0.5BW} S_{ref}(\omega c/2v)d\omega\end{array}\right]^2 = a(z)\left[\int_{BW} S_{ref}(\omega c/2v)d\omega\right]^2,$$

which is equal to the signal if all the light was detected by a single detector.

The Noise is the sum of the noise at each detector. The individual detector noise was $N_{shot}=0.5*P_{ref}*0.5*BW$. The sum of the noise of both detectors is $N_{shot}=0.5*P_{ref}*BW$ and the noise is half of what it was if the full spectrum or all the light was detected by a single detector. The SNR ratio in the case when each detector detects half the spectrum and the signal is coherently combined is,

$$SNR \propto \alpha(z)[\int S_{ref}(\omega c/2v)d\omega]^2/0.5*P_{ref}*BW=2P_{sample}/BW$$

Thus, the SNR is twice as high compared to if the full spectrum or all the light was detected by a single detector.

The gain in SNR is achieved because the shot noise has a white noise spectrum. An intensity present at the detector at frequency ω (or wavelength λ) contributes only to the signal at frequency ω, but the shot noise is generated at all frequencies. By narrowing the optical band width per detector, the shot noise contribution at each frequency is reduced, while the signal component remains the same.

Redundant SNR Arguments

The signal to noise can also be evaluated per frequency. The total SNR is given by,

$$SNR \propto \left[\int \sqrt{SNR(\omega)}\, d\omega\right]^2 = \frac{a(z)}{P_{ref} * BW}\left[\int S_{ref}(\omega c/2v) d\omega\right]^2$$

which defines a SNR density as

$$\sqrt{SNR(\omega)} \propto S_{ref}(\omega c/2v)\sqrt{\alpha(z)}/\sqrt{P_{ref}*BW},$$

which demonstrates that the SNR density at a particular frequency depends on the total pass band (BW) and the reference power of the signal at the particular detector.

For two detectors, where the spectrum is equally split over two detectors, the bandwidth BW is half, as is the reference power. For an individual detector in the two detector configuration the SNR density is given by,

$$\sqrt{SNR(\omega)} \propto S_{ref}(\omega c/2v)\sqrt{\alpha(z)}/\sqrt{0.5P_{ref}*0.5BW}$$

From the above equation, it is clear that the SNR density increases as the spectral bandwidth at the detector is decreased.

One embodiment of the system of the present invention is shown in FIG. **1**. The basic embodiment is an interferometer with a source arm, a sample arm, a reference arm, and a detection arm with a spectral demultiplexing unit, multiple detectors, optional analog processing electronics, and A/D conversion of all signals. The processing and display unit has optionally digital band pass filtering, Digital Fast Fourier Transforms ("FFT's"), coherent combination of signals, and data processing and display algorithms. The detector array may be 1×N for simple intensity ranging and imaging, 2×N for dual balanced detection, 2×N for polarization and/or Doppler sensitive detection, or 4×N for combined dual balanced and polarization and/or Doppler sensitive detection. Alternatively, an M×N array may be used for arbitrary M to allow detection of transverse spatial information on the sample.

Sources

The source arm contains a spatially coherent source that is used to illuminate the interferometer with low-coherence light. The source temporal coherence length is preferably shorter than a few microns (range is about 0.5 μm-30 μm). Examples of sources include, but are not limited to, semiconductor optical amplifier, superluminescent diodes, light-emitting diodes, solid-state femtosecond sources, amplified spontaneous emission, continuum sources, thermal sources, combinations thereof and the like.

Interferometer

The sample arm collects light reflected from the specimen and is combined with the light from the reference arm to form interference fringes. The reference arm reflects light back to be combined with the reference arm. This action of beam splitting/recombining may be performed using a beam splitter (Michelson), or circulator(s) (Mach-Zehnder) or other means known to those skilled in the art for separating a beam into multiple paths and recombining these multiple beams in a manner that interference between the beams may be detected. The splitting may be accomplished in free space or by using passive fiber optic or waveguide components.

Sample Arm

For LCI applications, the sample arm may be terminated by an optical probe comprising an cleaved (angled, flat, or polished) optical fiber or free space beam. A lens (aspherical, gradient index, spherical, diffractive, ball, drum) may be used to focus the beam on or within the sample. Beam directing elements may also be contained within the probe (mirror, prism, diffractive optical element) to direct the focused beam to a desired position on the sample. For OCT applications, the position of the beam may be changed on the sample as a function of time, allowing reconstruction of a two-dimensional image. Altering the position of the focused beam on the sample may be accomplished by a scanning mirror (such as, but not limited to, a galvanometer or piezoelectric actuator), electrooptic actuator, moving the optical fiber (rotating the optical fiber, or linearly translating the optical fiber). The sample arm probe may be a fiber optic probe that has an internally moving element where the motion is initiated at a proximal end of the probe and the motion is conveyed by a motion transducing means (such as, but not limited to, wire, guidewire, speedometer cable, spring, optical fiber and the like) to the distal end. The fiber optic probe may be enclosed in a stationary sheath which is optically transparent where the light exits the probe at the distal end.

Reference Arm Delay

A delay mechanism in the reference arm allows for scanning the length or the group velocity of the reference arm. This delay is produced by stretching ah optical fiber, free space translational scanning using a piezoelectric transducer, or via a grating based pulse shaping optical delay line. As opposed to traditional LCI or OCT systems described in prior art, the reference arm in the present invention does not necessarily need to scan over the full ranging depth in the sample, but is required to scan over at least a fraction of the ranging depth equal to one over the number of detectors. This feature of the present invention is fundamentally different from delay scanning schemes used in LCI and OCT systems disclosed in prior art. The delay line optionally has a mechanism for generating a carrier frequency such as an acoustooptic modulator, electrooptic phase modulator or the like. In order to reduce the scan range of the reference arm, the spectrum needs to be split into spectral bands according to a method that will be explained below.

Detection

In the detection arm a spectral demultiplexing unit demultiplexes the spectral components to separate detectors. The detectors may consist of photodiodes (such as, but not limited to, silicon, InGaAs, extended InGaAs, and the like).

Alternatively, a one or two dimensional array of detectors (such as, but not limited to, photodiode array, CCD, CMOS array, active CMOS array, CMOS "smart pixel" arrays, combinations thereof and the like) may be employed for detection. Two detectors for each spectral band may be used for polarization sensitive detection following separation of the recombined light into orthogonal polarization eigenstates. Detector arrays may be 1×N for simple intensity ranging and imaging, 2×N for dual balanced detection, 2×N for polarization and/or Doppler sensitive detection, or 4×N for combined dual balanced and polarization and/or Doppler sensitive detection. Alternatively, an M×N array may be used for arbitrary M to allow detection of transverse spatial information on the sample.

Detector signals are amplified by Trans Impedance Amplifiers ("TIA's"), band pass filtered (digitally or using analog circuitry) and digitized by A/D converters and stored in a computer for further processing. Each detector is preferably configured to be shot noise limited. Shot noise limited detection is achieved by adjusting the intensity of light returned from the reference arm so that the shot noise dominates over the thermal noise of the resistor in the TIA and is higher than the relative intensity noise ("RIN"). Each detector is balanced for such dual noise reduction.

In a broad aspect of the present invention, the number of detectors, N, can range from 2-10,000 or more. A preferred range of N is about 8-10,000 detectors. In one preferred embodiment, eight detectors (or a number in that area) can provide real time, or close to real time, imaging. When more than about one hundred detectors are used, it is likely that a custom array would need to be constructed.

Alternatively, another means for detection includes an integrating one-dimensional or two-dimensional CCD array which is capable of obtaining images at a rate greater than 1/f noise (approximately 10 kHz) (see FIG. **8**). In this case the TIA is not needed and the BPF can be implemented discretely following digitization. An additional modification to this method includes using a second CCD for balanced detection which allows increased reference arm power and acquisition speed due to reduction of RIN. This method could be implemented using a single CCD with dual-balanced detection enabled by either interleaving dual balanced rows of the array detector or by placing two similar CCD detectors adjacent to one another.

Processing

The signal of each detector is band pass filtered around the signal frequency, such as by FFT's. The signal of all detectors can be combined as explained hereinabove to obtain the complex cross spectral density in the frequency domain. By Fourier transform, the complex cross spectral density can be converted to a depth profile in the tissue. Several methods to process the complex spectral density to obtain depth profile information are included by reference.

System Integration

Processing of the multiple signals may be performed using an imaging or diagnostic console which performs basic operations including, mathematical image reconstruction, display, data storage. Alternatively, another embodiment, shown in FIG. **2**, envisions a standalone detection and processing system that may be connected to OCT and/or LCI systems already in use. In this case, the detector and digitization may be performed in the standalone unit. The input to the standalone unit would be the light combined from both reference and sample arms. The output of the system would be an interferometric signal similar to previous OCT or LCI console inputs, but with increased SNR. The standalone unit would contain the means for splitting the wavelengths into spectral bands, multiple detectors, analog electronics, including TIA's and means for reconstructing the interferometric signal. The means for reconstructing the interferometric signal would include either analog or digital means where the analog means includes band pass filters ("BPF's"), and analog means for adding the individual interferograms from each wavelength band. Digital means would include an analog to digital converter, CPU capable of recombining the interferograms from each spectral band into a single full bandwidth interferometric signal. The reconstructed interferogram may be then the output of the standalone system or alternatively, the reconstructed interferograms demodulated signal may be used as the input to the pre-existing system console.

Scan Range of the Reference Arm

The ranging depth in the sample is determined by the resolution with which the cross spectral density can be determined. In a method using a single detector the spectral resolution of the complex spectral density is determined by the scan range of the reference arm. The larger the scan range, the higher the spectral resolution and the larger the ranging depth in the sample. In a system with a spectral demultiplexing unit and multiple detectors, the resolution of the cross spectral density is a combination of reference arm scan range and spectral demultiplexing characteristics.

Any suitable wavelength band shape may be used for demultiplexing. For arbitrary spectral band shapes, the scan range of the reference arm is determined by the maximum path length delay that is needed to completely resolve the spectral components in each band. In cases where the wavelength band is determined by successive non-overlapping optical bandpass filters, a full scan length is needed and the SNR improvement is achieved by decreasing the width of the BPF for each spectral bands.

For instance, in one preferred embodiment, as depicted in FIG. **3**, the spectral demultiplexing unit can split the spectrum into two bands where each band consists of a set of narrow spectra in a comb-like structure. Interleaving the comb-like spectral bands of each detector gives back a continuous spectrum. The resolution needed to resolve the spectrum at an individual detector is half of what it would need to be in a single detector system, and thus the scan range of the reference arm can be reduced by a factor of two, while maintaining the same ranging depth in the sample. In an alternative embodiment, the spectral demultiplexing unit can be in the reference arm. In FIG. **4** an example is shown for splitting up the spectrum in four spectral bands. In this example the scan range of the reference arm can be reduced by a factor of four while maintaining the same ranging depth in the sample.

Embodiments of the Demultiplexing Filter

Several techniques are known to demultiplex or disperse the spectrum. One method would use a grating and a micro lens array to focus spectral components onto individual detectors. A second method would use prisms instead of a grating. A third method would use a grating and an addressable mirror array (such as, but not limited to, a "MEMS" mirror or digital light processing "DLP" apparatus or the like) to direct spectral components to individual detectors. A fourth method would use a linear array of optical filters prior to the array of individual detectors. A fifth method would use waveguides etched into a material or manufactured from fiber optic components to generate a pattern with the desired filter action. As an example, in FIG. **4** an embodiment of a wave guide filter is drawn that will split the spectrum into bands. A sixth method would use arrayed waveguide gratings ("AWG") to create the interleaved or arbitrary spectral bands.

Relative Intensity Noise

One of the noise terms that are present at the detectors is relative intensity noise ("RIN") or Bose-Einstein noise. For a system where the sample arm optical power is negligible compared to the reference arm optical power at the detectors, RIN will become dominant for spectral widths less than a few nanometers at trans impedance amplifier bandwidths of 1 MHz. For many detector configurations, the spectral width at each detector will be smaller than a few nanometers, and the relative intensity noise will dominate the overall system noise. Thus, balanced detection needs to be implemented to eliminate the RIN. Several methods known in the art exist to implement balanced detection. One method will be discussed in more detail. Light from the reference arm and sample arm is incident on a grating at slightly different angles and reflected and focused onto a linear N×M photo detector array. Along the N direction (column) of the array, wavelength is encoded. Along the M direction (row) of the array, the interference pattern of the sample and reference arm at a particular wavelength is recorded. Since sample and reference arm light were incident at slightly different angles, a pattern of interference maxima and minima will be present in the column direction. Balanced detection can be implemented by subtracting diode signals that are exactly out of phase with respect to the maxima and minima pattern. Alternatively, balanced detection can be implemented by measuring the amplitude of the interference pattern in the column direction which may be accomplished by subtracting the maxima or the interference pattern from the minima of the interference pattern along the column.

Signal Processing to Reconstruct the Signal after Spectral Demultiplexing and Detection

Two cases will be discussed as nonlimiting illustrations of the present invention, firstly the case of continuous spectral bands (blocks), and secondly the comb-like spectral bands as depicted in FIGS. **2** and **3**.

Case A: Continuous spectral bands.

The detection arm light is split into N spectral blocks, where each spectral block contains the intensity between two optical frequencies,

$$B_N = \int_{\omega_N}^{\omega_{N+1}} S_{ref}(\omega c/2v)d\omega$$

The signal for the full spectral width is obtained by an FFT of the signal in each band, an optional compensation of dispersion and other corrections to the phase and amplitude of each Fourier component to optimize the signal and to correct the spectral density for side lobe reduction, addition of the complex FFT spectra, and inverse FFT on the added complex FFT spectrum, optionally with data reduction before the inverse FFT, to obtain the optionally demodulated function R(t), which is the interferometric response for a depth scan with the full source spectrum.

Case B: Comb like spectral bands and the reconstruction of the full depth range in the sample arm from reduced reference arm scans.

The following discussion describes the principle of reconstruction of the full depth range in the sample arm from reduced reference arm scans. The procedure will be explained in the case of demultiplexing the spectrum in two spectral bands. The method can be expanded for demultiplexing into many spectral bands.

The signal at the detector for a single detector system is given by R(t). The depth range in the sample is given by the measurement time T of a single A-line (depth profile) times the group velocity generated by the reference arm delay line,

$$z_{range}=v_g T$$

The smallest resolvable frequency after an FFT is given by 1/T, which gives a smallest resolvable angular frequency $\Delta\omega=2\pi/T$. The filter as depicted in FIG. **4** splits the signal into two bands with peaks at $\omega=\omega_0,\omega_0+2\Delta\omega,\omega_0+4\Delta\omega$, etc. and $\omega=\omega_0+\Delta\omega,\omega_0+3\Delta\omega$, etc., respectively.

$B_1(t)$ and $B_2(t)$ are the signals in band one and two respectively. The signal in spectral bands one and two after Fourier transform are given by $B_1(\omega)=R(\omega)\cos^2(\omega T/4)$ and $B_2(\omega)=R(\omega)\sin^2(\omega T/4)$.

This product in the Fourier domain can also be written as a convolution in the time domain. Assuming the signals periodic with time T, the signals $B_1(t)$ and $B_2(t)$ are given by $B_1(t)=R(t)+R(t+T/2)$ and $B_2(t)=R(t)-R(t+T/2)$.

Using the above equations, the signal R(t) from t=0 to t=T can be reconstructed from the signals $B_1(t)$ and $B_2(t)$ recorded from t=0 to t=T/2 by writing,

$R(t)=B_1(t)+B_2(t)$ and $R(t+T/2=B_1(t)-B_2(t)$ for $0<t<T/2$. For higher N>2, the identical procedure is performed such that R(t) is reconstructed from B_1 to B_N.

This demonstrates that the signals $B_1(t)$ and $B_2(t)$ only need to be recorded over half the depth range z_{range}. Thus, the depth ranging in the reference arm can be reduced by a factor of 2 while the ranging depth in the sample remains the same. If the signal is split into more spectral bands, like shown in FIG. **3**, a similar procedure as described above allows reduction of the depth scan in the reference arm by a factor of N, while the ranging depth in the sample remains the same, and N the number of spectral bands.

A flow diagram of the procedure described above is given in FIG. **7**.

Case B2. Limit of Large Number of Spectral Bands

In the limit of a large number of spectral bands,

$$N \geq \frac{L}{\lambda},$$

the optical path length change in the reference arm approaches that of a wavelength, λ. In this limit, only a phase change across one wavelength is needed for reconstructing the entire axial scan over length L. In this case, the reference arm path delay may be accomplished by using any of the aforementioned means for scanning the reference arm delay. Other preferred methods include insertion of an electrooptic modulator, acoustooptic modulator or phase control rapidly scanning optical delay line ("RSOD") in the reference arm path to impart the path length delay of one wavelength. Also in this case, the wavelength demultiplexing unit does not separate the wavelengths into a comb pattern, but demultiplexes the spectrum into unique optical frequencies, with each frequency detected by a single detector.

Case C. Fourier Domain Reconstruction for Arbitrary Wavelength Patterns

As opposed to reconstruction of the LCI or OCT signal in the time or space domains, the signal may be reconstructed in the Fourier domain by adding the complex spectral components for each wavelength band to compose the Fourier transform of the LCI or OCT signal. Alterations of the phase for each Fourier component may be needed in some circumstances to correct for minimization of reference arm delay length.

Reconstruction of the Image or One Dimensional Axial Scan

Following reconstruction of the LCI or OCT signal in the real domain, the axial reflectivity may be determined by demodulating the reconstructed LCI or OCT signal. Means for demodulation include, multiplication by a sinusoid and low pass filtering, envelope demodulation using envelope detection, square law demodulation and low pass filtering, quadrature demodulation followed by FIR, IIR filtering, or low pass filtering. In addition, known to those skilled in the art, is reconstruction of Stokes vectors (polarization) and flow from these LCI or OCT signals. Following reconstruction and demodulation, the data may be displayed in one or two-dimensional format (image) for interpretation and ultimately diagnosis of a tissue condition or defect in a medium. If one reconstructs the LCI or OCT signal in the Fourier domain, the reconstructed signal in the Fourier domain can be demodulated in the Fourier domain by shifting the Fourier spectrum and performing an inverse Fourier transform. As a result, the complex signal in the real domain (quadrature signal) is then reconstructed into axial reflectivity information by computing the amplitude of the real portion of the quadrature signal. The complex component is used for computing polarization or flow information. Alternatively, if the signal is reconstructed in the Fourier domain, it can be directly inverse Fourier transformed into the real domain and undergo the aforementioned processing described for the reconstructed real domain signals.

ADVANTAGES

The present invention reduces shot noise which allows for much lower source powers, or much higher acquisition rates than current systems. The increased detection sensitivity allows for real time imaging. Such imaging speed can help practitioners where motion artifacts are a continuing problem, such as in gastrointestinal, ophthalmic and arterial imaging environments. By increasing the frame rate while maintaining or improving the signal to noise ratio such artifacts can be minimized.

The invention will be further described in connection with the following examples, which are set forth for purposes of illustration only.

EXAMPLE

The method was verified in the lab by the following experiment.

In the existing OCT system, the shot noise power spectrum as determined from the spectral density due to the reference arm optical power was measured. Then ⅔ of the spectrum from the reference arm was blocked, and experimentally it was verified that the shot noise power spectrum was reduced by a factor of three, thus demonstrating that the shot noise is reduced by a factor of 3 if the spectrum is split in three spectral bands (see FIG. **5**). The upper curve (gray dotted line) shows the power spectrum for the OCT signal with one detector. For the lower curve (solid line), the spectrum was limited by ⅓ with a corresponding factor of 3 improvement in signal to noise ratio. This data was generated by experiment, blocking ⅔ of the spectrum in a grating-based double-passed pulse shaping rapidly scanning optical delay line.

An object with low reflectivity was inserted in the sample arm. Using the full spectral width of the source, the power spectrum of the interference between sample and reference arm light was determined in the lower half of the spectral density. Then the upper part of the source spectrum was blocked in the reference arm, and it was verified that the lower ⅓ of the power spectrum of the interference between sample and reference arm light had the same magnitude as in the previous measurement (see FIG. **6**). This figure demonstrates that the signal amplitude is equal for the N=1 and N=⅓ cases where they overlap. The result of equal amplitude signal for N=⅓ case and the 3-fold lower noise for the N=⅓ case (see FIG. **2**) demonstrates that splitting into N wavelength bands increases the SNR by a factor of N.

This demonstrates that when the light in the detection arm is split in two spectral bands, the spectral density of the interference between sample and reference arm light within the spectral bandwidth of a single detector is unchanged. Combined with the measurement that showed a reduction in the shot noise power spectrum, the conclusion is that a reduction of shot noise can be realized by splitting the detection arm light in separate spectral bands.

Although only a few exemplary embodiments of this invention have been described in detail above, those skilled in the art will readily appreciate that many modifications are possible in the exemplary embodiments without materially departing from the novel teachings and advantages of this invention. Accordingly, all such modifications are intended to be included within the scope of this invention as defined in the following claims. It should further be noted that any patents, applications and publications referred to herein are incorporated by reference in their entirety.

What is claimed is:

1. An apparatus for optical imaging, comprising:

a) an interferometer configured to receive at least one electro-magnetic radiation from a transmissive reference, and generate the at least one signal at least one signal as a function of the at least one electro-magnetic radiation;

b) a spectral separating unit which splits the at least one signal received from the interferometer into a plurality of optical frequencies; and

c) a plurality of detectors, each detector being configured to detect at least a portion of the optical frequencies received from the spectral separating unit, wherein the spectral separating unit comprises at least one of (i) an addressable mirror array or (ii) a waveguide filter.

2. The apparatus according to claim **1**, wherein the spectral separating unit splits the signal into the bands.

3. The apparatus according to claim **1**, wherein the detectors are provided in a form of a two-dimensional array.

4. The apparatus according to claim **1**, wherein a sample is scanned in a series of simultaneous illuminations of substantially all of areas of the sample to provide at least one radiation associated with the sample to be used by the interferometer to provide the at least one signal.

5. The apparatus according to claim **1**, wherein the interferometer comprises an arrangement generating a path length difference that is a fraction of a ranging depth of the interferometer.

6. An apparatus for optical imaging, comprising:

a) an interferometer structured to provide at least one signal;

b) a spectral separating unit which splits the at least one signal received from the interferometer into a plurality of optical freguencies; and

c) a plurality of detectors, each detector being configured to detect at least a portion of the optical freguencies received from the spectral separating unit, wherein the spectral separating unit comprises at least one of (i) an addressable mirror array or (ii) a waveguide filter, wherein the spectral separating unit comprises a polarization separating unit.

7. An apparatus for optical imaging, comprising:
a) an interferometer structured to provide at least one signal;
b) a spectral separating unit which splits the at least one signal received from the interferometer into a plurality of optical freguencies;
c) a plurality of detectors, each detector being configured to detect at least a portion of the optical frequencies received from the spectral separating unit, wherein the spectral separating unit comprises at least one of (i) an addressable mirror array or (ii) a waveguide filter; and
d) an arrangement which configured to at least one of:
  i. reconstruct the signal from the detectors by a mathematical manipulation of each plurality of signals obtained from the detectors, or
  ii. track a phase of the signal of the interferometer.

8. An apparatus for optical imaging, comprising:
a) an interferometer structured to provide at least one signal;
b) a spectral separating unit which splits the at least one signal received from the interferometer into a plurality of optical frequencies; and
c) a plurality of detectors, each detector being configured to detect at least a portion of the optical frequencies received from the spectral separating unit, wherein the spectral separating unit comprises at least one of (i) an addressable mirror array or (ii) a waveguide filter, wherein the spectral separating unit splits the signal into a plurality of bands, whereby at least one of the bands comprises spectra that has a comb-like structure.

9. An apparatus for optical imaging, comprising:
a) an interferometer structured to provide at least one signal;
b) a spectral separating unit which splits the at least one signal received from the interferometer into a plurality of optical frequencies;
c) a plurality of detectors, each detector being configured to detect at least a portion of the optical frequencies received from the spectral separating unit, wherein the spectral separating unit comprises at least one of (i) an addressable mirror array or (ii) a waveguide filter; and
d) an arrangement which configured to track a phase of the at least one signal of the interferometer.

10. An apparatus for optical imaging, comprising:
a) an interferometer structured to receive at least one electro-magnetic radiation from a reference and provide at least one signal;
b) a spectral separating unit which splits the at least one signal received from the interferometer into a plurality of optical frequencies; and
c) a plurality of detectors, each detector being configured to detect at least a portion of the optical frequencies received from the spectral separating unit, wherein the spectral separating unit comprises at least one of (i) an addressable mirror array or (ii) a waveguide filter.

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